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Compositional Analysis and Classification of Projectile Residues in LDEF Impact Craters

Friedrich Horz
Ronald P. Bernhard

June 1992



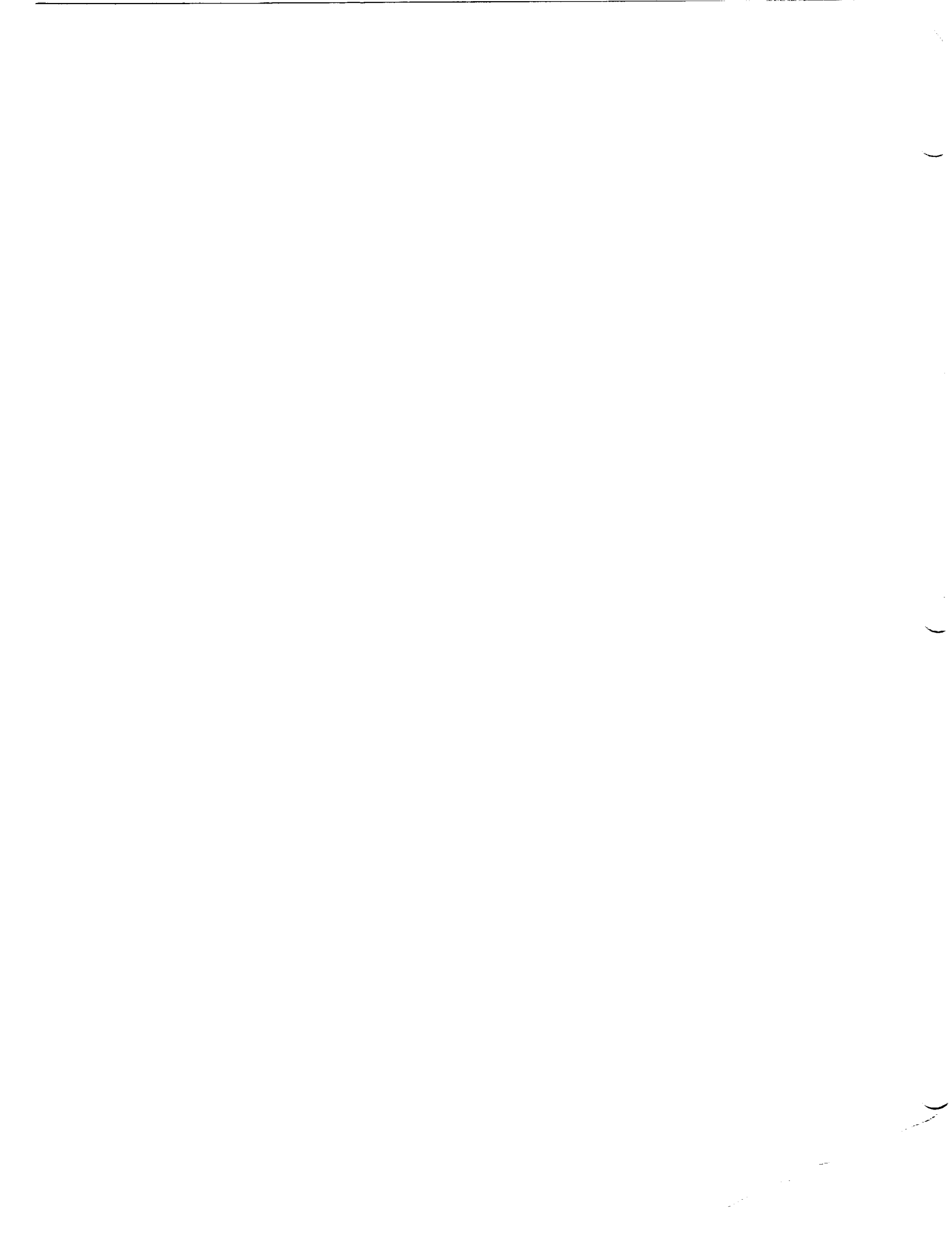
(NASA-TM-104750) COMPOSITIONAL
ANALYSIS AND CLASSIFICATION OF
PROJECTILE RESIDUES IN LDEF IMPACT
CRATERS (NASA) 209 p

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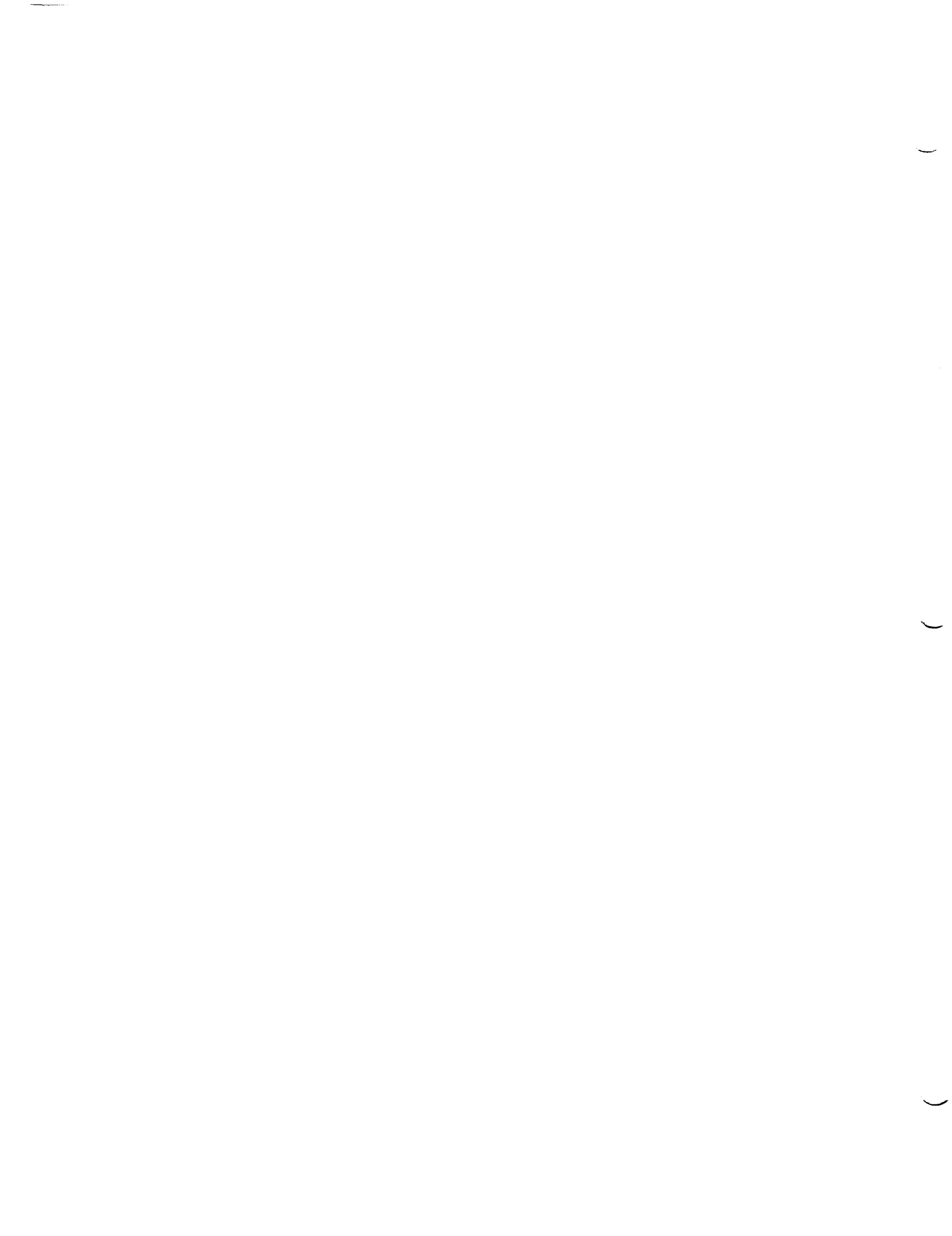
Compositional Analysis and Classification of Projectile Residues in LDEF Impact Craters

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INTRODUCTION

The Long Duration Exposure Facility (LDEF) provides an unprecedented opportunity to study the hypervelocity particle environment in Low Earth Orbit (LEO). The total surface area exposed was some 130 m² and total mission duration some 5.7 years, yielding time-area products almost 2 orders of magnitude larger than all previous opportunities combined to study hypervelocity damage and impact features on surfaces retrieved from space. While most surfaces were dedicated to investigate a diversity of environmental effects, some 30m² were planned on LDEF to characterize the hypervelocity particle environment (Levine, 1992).

Typical crater or penetration hole investigations concentrate on their size-frequency and areal density in support of particle flux measurements (e.g. Humes, 1992), on specific collisional damage caused to a variety of materials and on the chemical and isotopic composition of projectile residues associated with individual impact features (e.g. Amari et al, 1992). Among those instruments concentrating on the compositional make-up of the hypervelocity particles in LEO was the "Chemistry of Micrometeoroids" experiment (CME or AO187-1; Horz et al, 1992). These particles are expected to originate from a variety of natural sources, such as comets and asteroids, as well as from man-made sources, such as accidental spacecraft explosions or as byproducts of spacecraft operations, e.g. solid fuel rocket firings or waste-dumps. The primary objective of CME concentrates on natural cosmic dust particles as representatives of early solar system processes (e.g. Kerridge and Matthews, 1988).

Analyses of such particle residues are time consuming owing to the small sample mass, frequently < 10-10 g. Nevertheless a variety of analytical methods are available and in many cases it is even desirable to employ a variety of complementary methods on a single specimen. For example, if only melt were found lining the crater bottoms and walls, the analysis methods and procedures would differ from a case where unmelted impactor fragments are preserved; the latter would attempt detailed phase characterization and delineation of textural relationships. Clearly, it is not practical -nor necessary- to investigate every single impact in identical, detailed fashion; such detailed characterization can only be performed on a high graded, representative population of crater residues. It becomes necessary, therefore, to perform survey-type investigations that can reveal in qualitative fashion the diversity of particle types present and

identify those features worthy of detailed effort. This survey-type preliminary investigation must be performed in systematic fashion over a randomly selected population of craters.

This document details the results of such a compositional survey and illuminates the substantial variety of particle types that exist in LEO. Specifically we present a survey type study of craters in high purity gold (> 99.99% Au) substrates that were exposed by instrument AO187-1 on LDEF's trailing edge, location AO3. This gold substrate was approximately 0.8m² in surface area and 0.5 mm thick. No penetrative impact event(s) were observed in these gold sheets and all impact features are microcraters, the larger ones approaching mm in diameter. The total surface area was composed of 7 individual gold panels, 6 of which were surveyed in detail. They contain a total of 198 craters > 20 um in diameter, all of which were subjected to the above described survey activity.

Those familiar with small-scale impact cratering will notice a distinct dichotomy in crater morphology. Most craters appear normal, yet a fair number possess unusual morphologies, characterized by delamination and substantial peeling of material, giving rise to petalled craters and rims. This atypical morphology seems to be caused by structural heterogeneities of the gold substrate, produced by rolling. It appears that layers a few micron thick were smeared from topographic highs into lows during this rolling process, yet did not bond completely to form a physically homogeneous target. Interestingly, we observed the initial surface onto which the last rolling operation deposited the thin, relatively weakly bonded layers, to be characterized by particularly high (surface) contaminants, on occasion, suggesting again that some old surface was covered by material of high intrinsic purity. Specifically, As levels on this surface can be substantially above background, although contamination is by no means limited to As.

The purpose of this report is to present in catalog form our survey type findings on an unbiased set of impact features, because every crater observed optically on these gold-substrates was analyzed. The principle compositional information is in the form of energy-dispersive X-ray spectra, the most widely applied survey method. These spectra are qualitative and establishment of particle types and especially of source area, .i.e. "natural" versus "man-made" is a highly interpretative matter. In many cases such distinctions are made readily, yet transitional cases exist where X-ray spectra alone may not suffice. Detailed classification of LDEF-particle-types and their compositional grouping/source assignment is just emerging. The specific goal of this report is to contribute to ongoing efforts in establishing such classifications, by presenting our evidence and criteria pertaining to compositional groups and classes of particles. We encourage

critique and comments by others, because a common set of criteria must be developed by all LDEF workers to classify all LDEF projectiles in systematic fashion.

The actual classification proposed in this document was largely developed and adopted from the analyses of space-exposed surfaces retrieved during the repair of the **Solar Maximum** satellite (e.g. Rietmeijer et al, 1986, Laurance and Brownlee, 1986, Warren et al, 1989) and **Palapa** (Bernhard, 1990). The latter in turn leans heavily on the criteria adopted during the preliminary analysis of compositionally diverse **particulates recovered from the stratosphere** via high altitude U2 or ER2 aircraft (e.g. Brownlee, 1985, Mackinnon and Rietmeijer, 1987, or Bradley et al., 1988). Lastly, the format of the catalog is patterned after the catalogs produced periodically following preliminary analysis of the stratospheric particle collections (Zolensky et al, 1990).

SAMPLE PROCESSING AND ANALYSIS

Experiment surfaces from A03 were stored, scanned, and processed in the Facility for the Optical Inspection of Large Surfaces (FOILS Lab) at the Johnson Space Center. Each of the 7 gold panels (57 x 20.6cm) were optically scanned at 80x using a Leitz M8 stereo microscope and computer-aided imaging/digitization system. Craters were located, measured, and labeled with a feature number adjacent to the impact. The impacts were then punched from the plates using a hand operated punch/die press and the core number was etched onto the back of each disk. Samples are 1.6cm in diameter and 0.5mm thick. Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDXA) was conducted on each feature to determine its origin.

SEM imaging was performed with an ISI-SR50 at an accelerating voltage of 25Kv. Images are therefore relatively high in contrast and resolution (low voltages result in relatively lower contrasts and lower resolutions). Each sample was surveyed at high magnification for possible projectile remnants. The high contrast conditions simplified the task of separating the brighter target melt from the darker (in most cases) projectile melt. EDXA data were collected using a Si(Li) detector on a LINK eXL analyzer (detector 90 degrees from beam path). Because of the equipment setup and the sample (crater) geometry, a 30 degree sample tilt, high accelerating voltage, and long count times were used to insure maximum efficiency. Because of the nature of high velocity collision, many of the impacts were void of obvious projectile residues and contained only vapor coatings left by impacting projectiles. X-ray spectra were collected and recorded over a 0-20 KeV range, count times vary for 100 - 4000 seconds. In some cases,

system (artifact) peaks appear in the spectra due to acquisition geometries and are expected. Low levels of contamination are also present as Silicon and in some impacts Arsenic (probably from surface manufacturing).

CATALOG FORMAT

Each page in the main body of the catalog is devoted to one impact and consists of SEM (SEI) image, an EDXA spectrum, and a brief summary of preliminary examination data obtained. Component (E00E-E00K) depicts the gold plate on which the impact was detected. The feature number identifies the crater as detected during optical scanning, the core number identifies the curated sample disk on which the crater resides. The diameter is in micrometers and is measured optically rim-to-rim. Spectrum are normalized to 4000 counts and are typical of residues found in the associated impact.

RESULTS

The survey-type data and interpretations are summarized in Figure 1. Some 30% (N=57) of all impactors are interpreted to be natural cosmic dust, some 15% (N=30) projectiles are interpreted as man-made, and some 50% of all craters analyzed did not contain detectable residues at the sensitivity level of the SEM EDXA method employed.

Three major subclasses can be distinguished among the natural projectiles:

1) CHONDRITIC

These contain Si, Mg, and Fe as major components with minor quantities of Al, Ca and S; the latter may not be present all the time. Typically, these residues are melts that contain very little clastic material, if any. They seem to derive from fine-grained, compound aggregates of chondritic bulk composition.

2) MONOMINERALIC SILICATES

These contain Si, Mg, Ca and Fe in variable proportions typical for mafic silicates, such as olivine or pyroxene. While also mostly molten, some of these craters contain fragments of the above minerals, typically in clusters, i.e. fragments of a larger parent-crystal. Some of the melts have chondritic composition, indicating that the large crystals resided in a fine-grained, chondritic matrix. All craters that contain unmelted fragments are relatively shallow, suggesting low-velocity impacts.

3) NI-FE SULFIDES

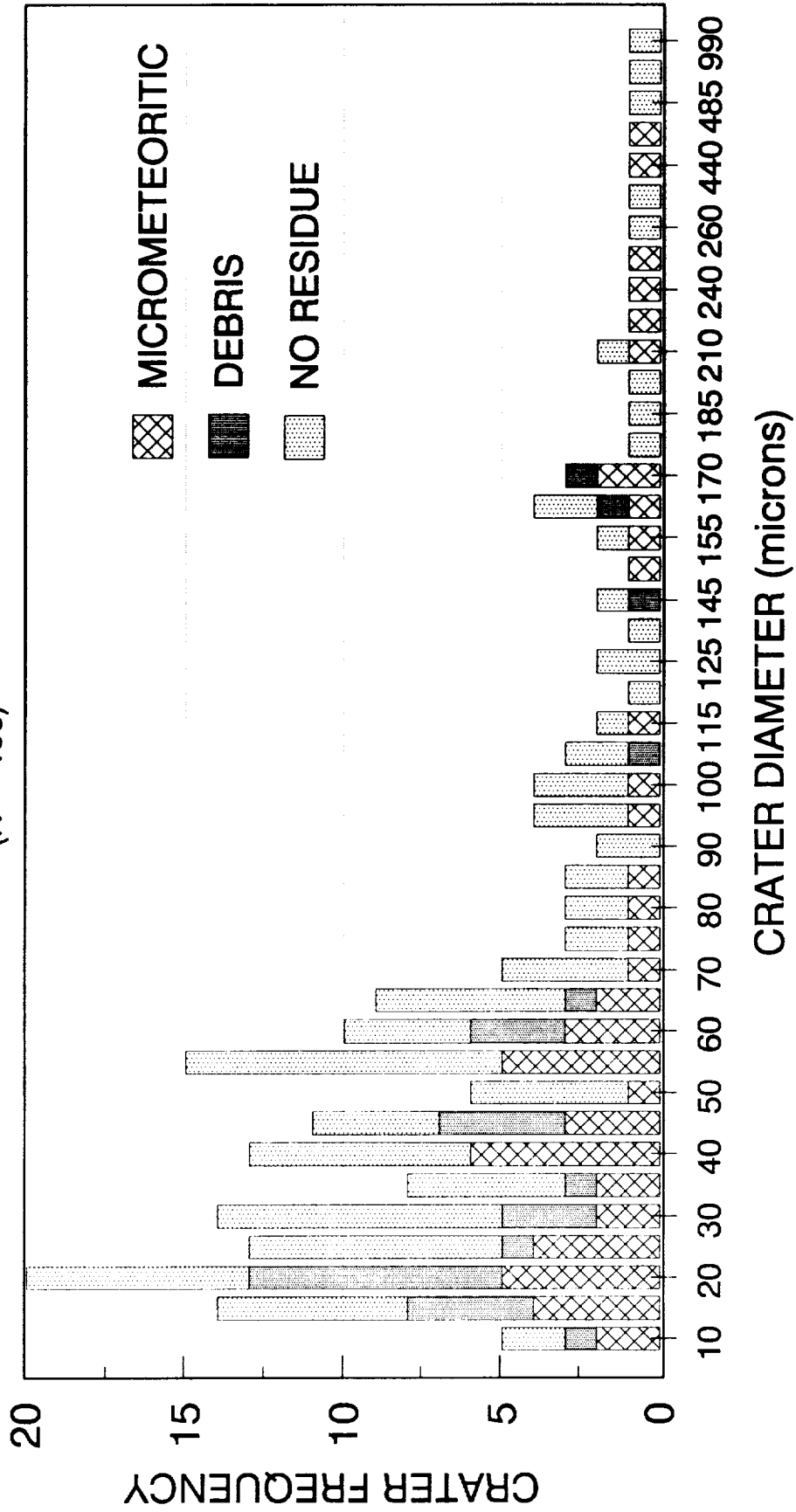
These are also, in essence, monomineralic projectiles composed of Ni-Fe rich sulfides, a major mineral in carbonaceous and other meteorites.

The population of man-made particles is variable as well, although the majority (N=25) seems to be made up of Al only, and could be caused either by Al₂O₃ spheres from solid rocket exhausts or from structural aluminum-fragments. This is the first time that aluminum could be demonstrated to be the dominant species, owing to the favorable composition of the "collector" substrate, i.e. the Au-background. Two craters contained stainless steel signatures (Fe, Ni, Cr) and one each was a paint flake (Ti, Zn, Al), a solder-speck (Ag) and some electronic components (Cu). The total number of man-made impactors is unexpectedly high for the trailing edge of a non-spinning platform, such as LDEF, and suggests that highly elliptic particle orbits, consistent with geostationary satellites or their transfer vehicles, were underestimated in the past.

Some 50% of all craters contain no residue, despite considerable analytical efforts. The associated projectiles must have vaporized leaving either no trace or sufficiently thin vapor deposits only that are beyond detection. Considerable effort was spent on experimenting with diverse electron beam settings and other instrument parameters to increase the yield of "analyzable" projectile residues, yet 50% of all impacts left no signature, unfortunately.

A03 GOLD

(N = 198)

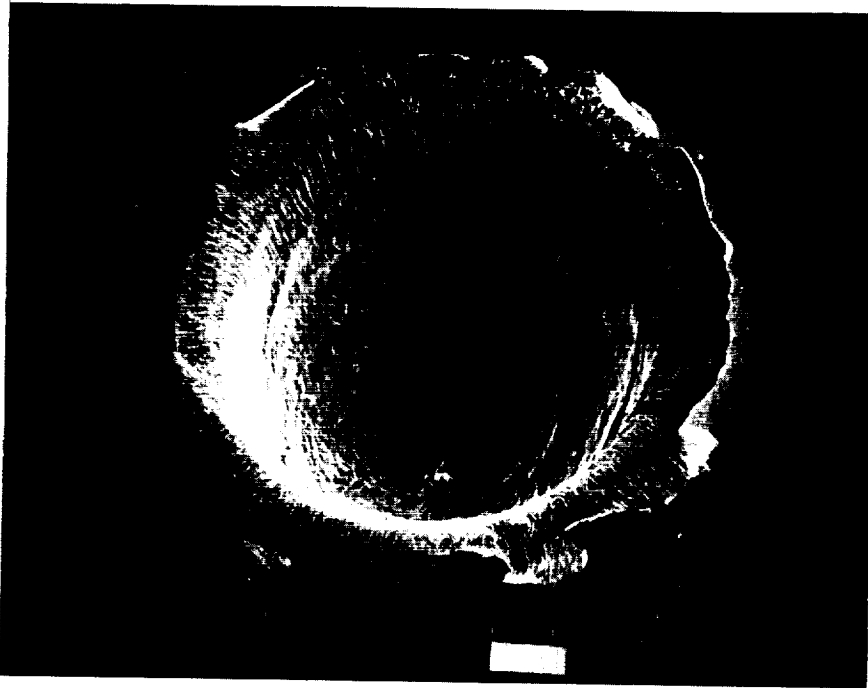


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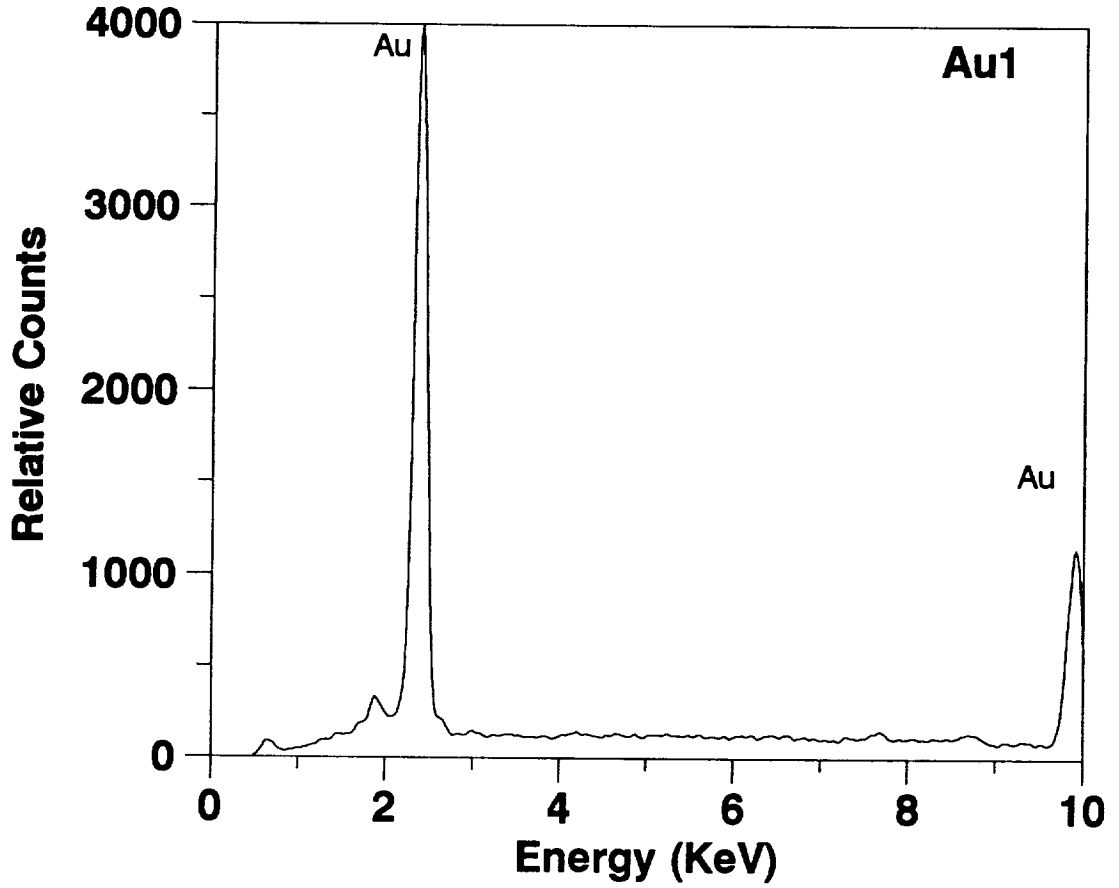
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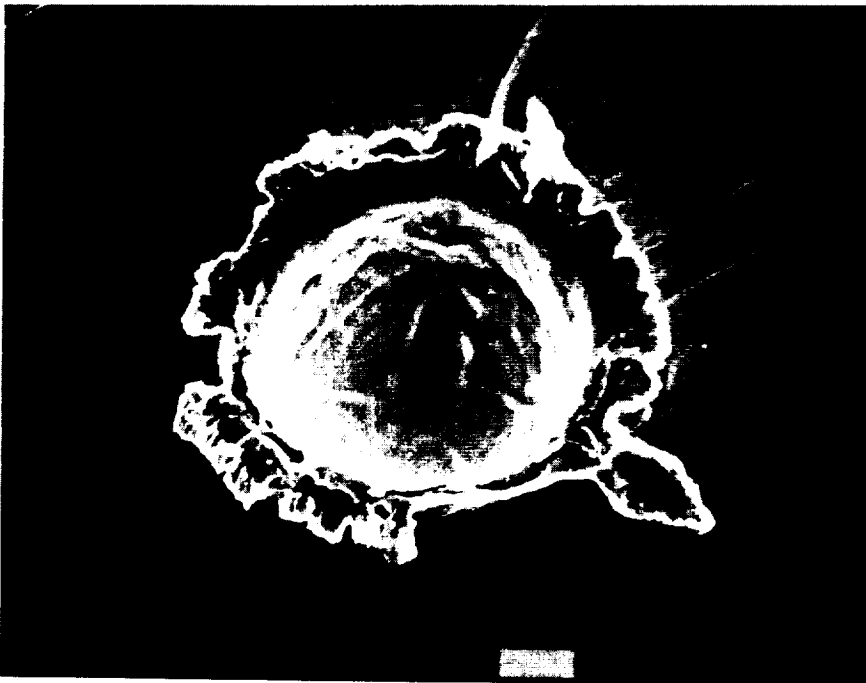


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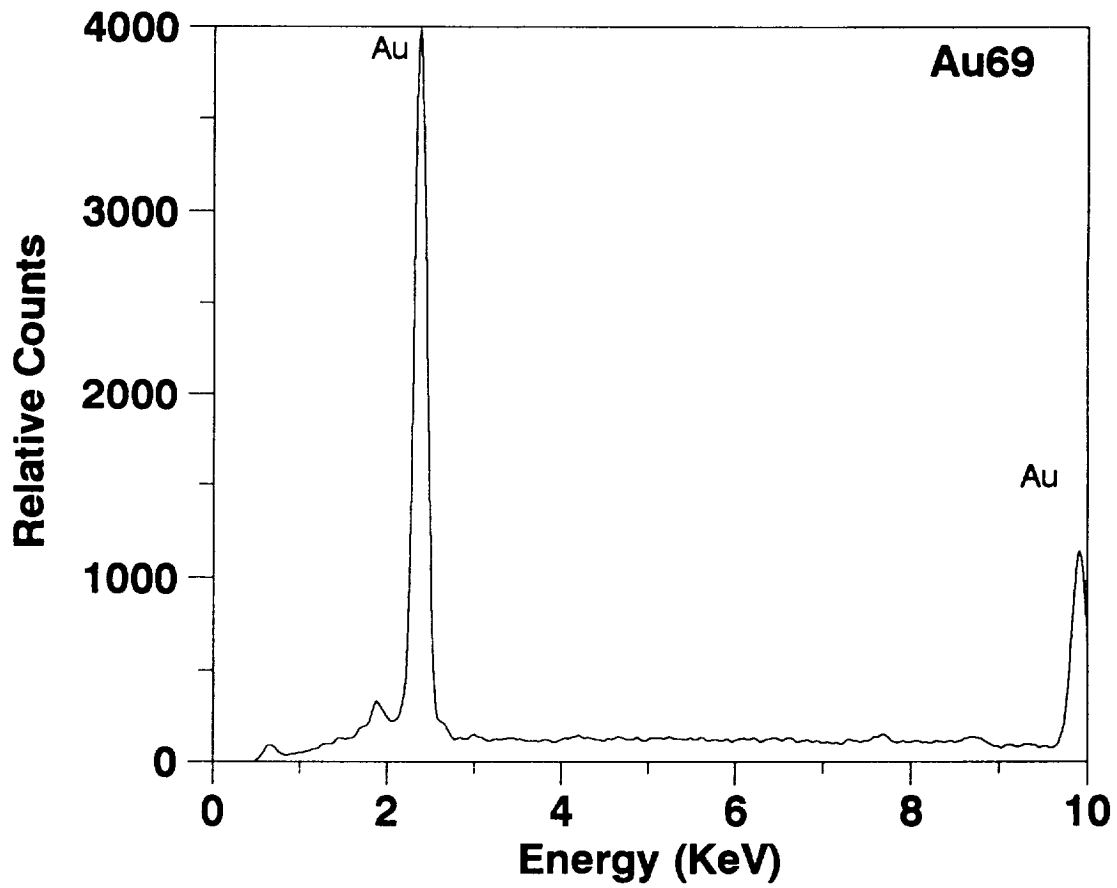
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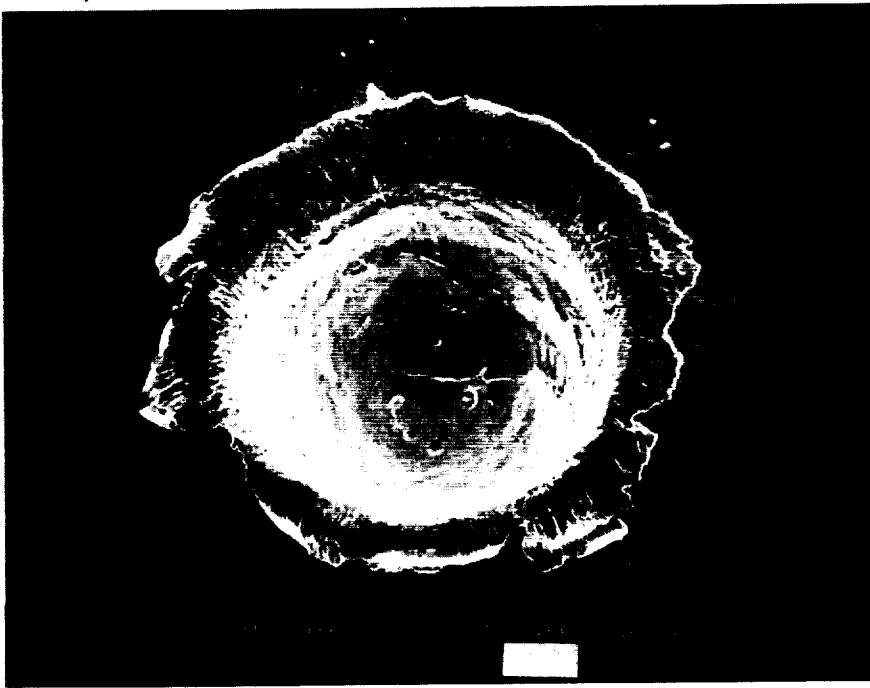
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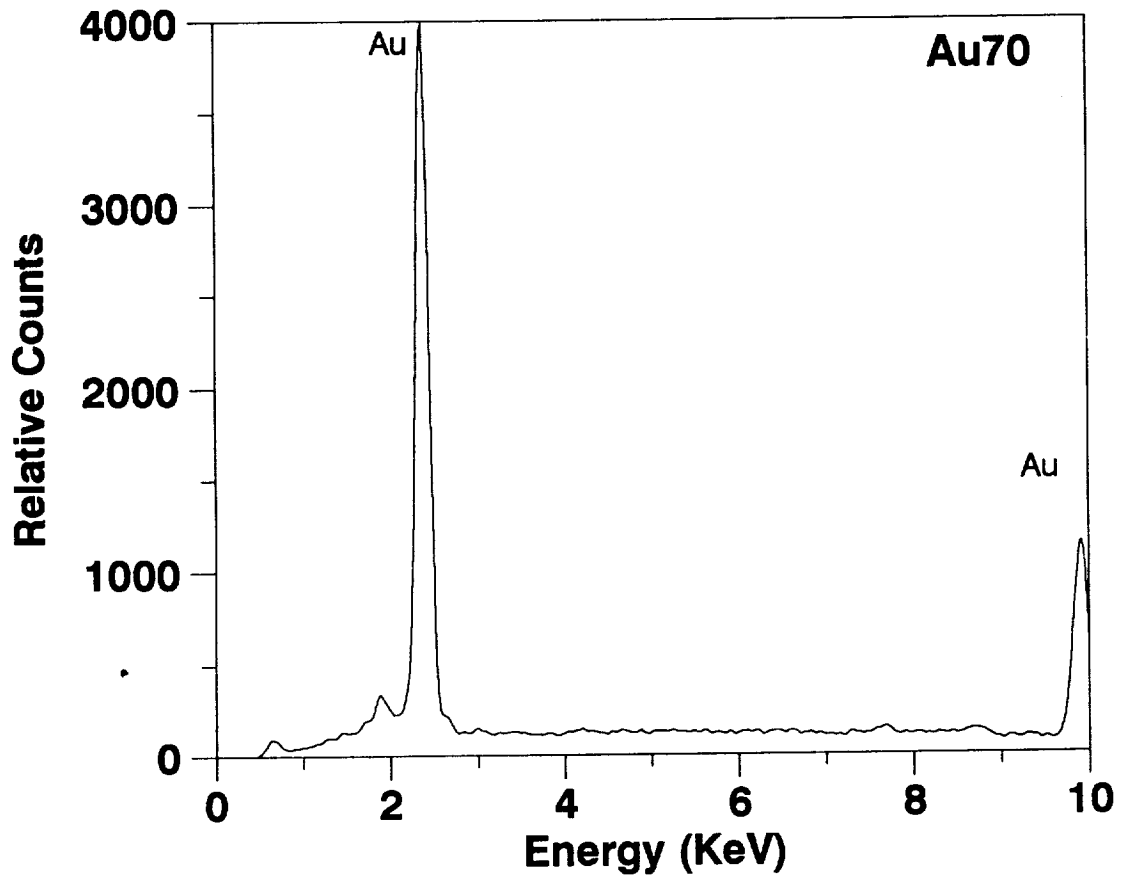


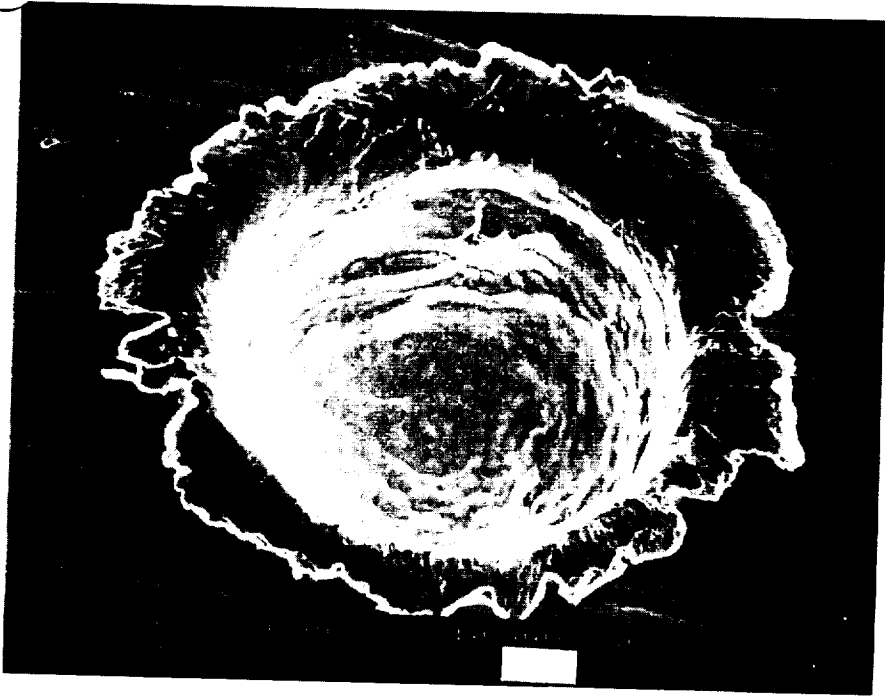
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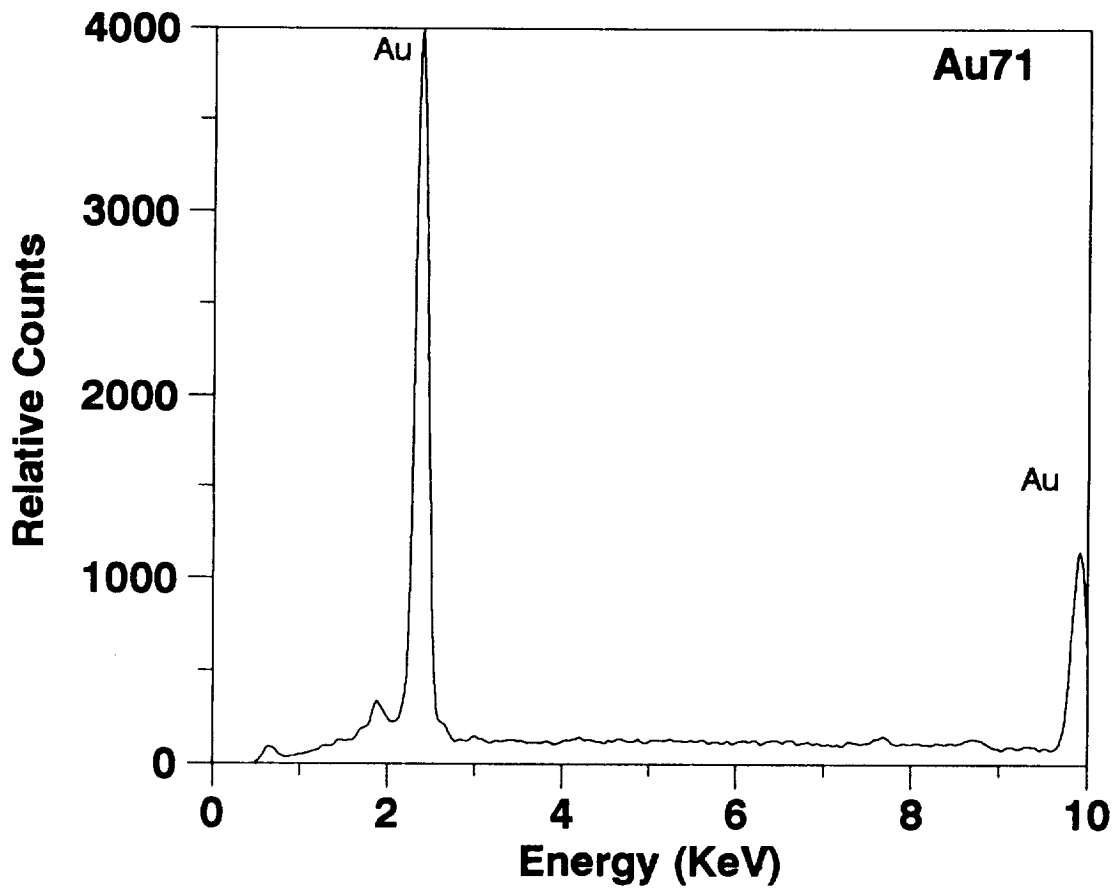
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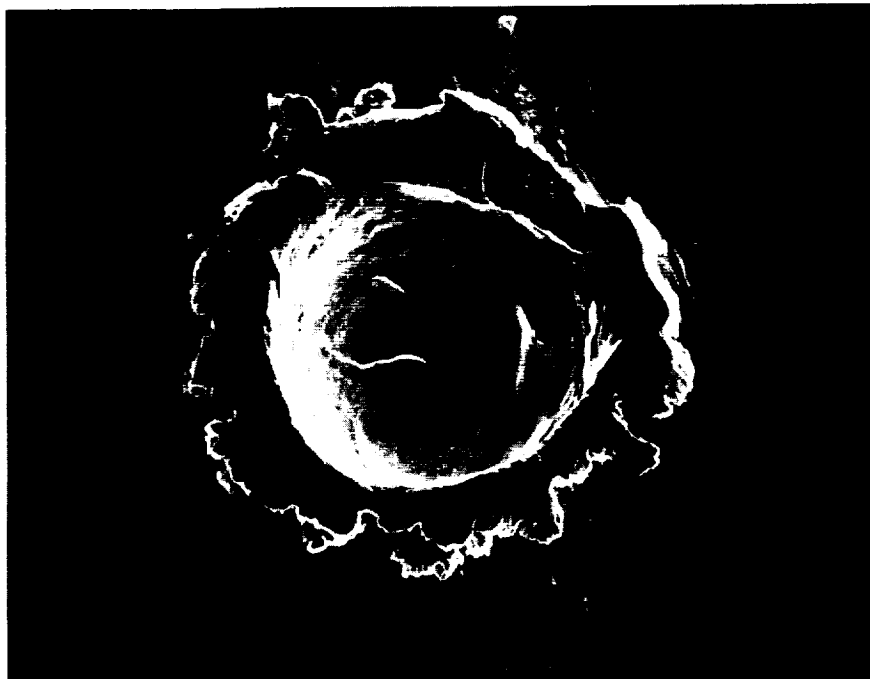
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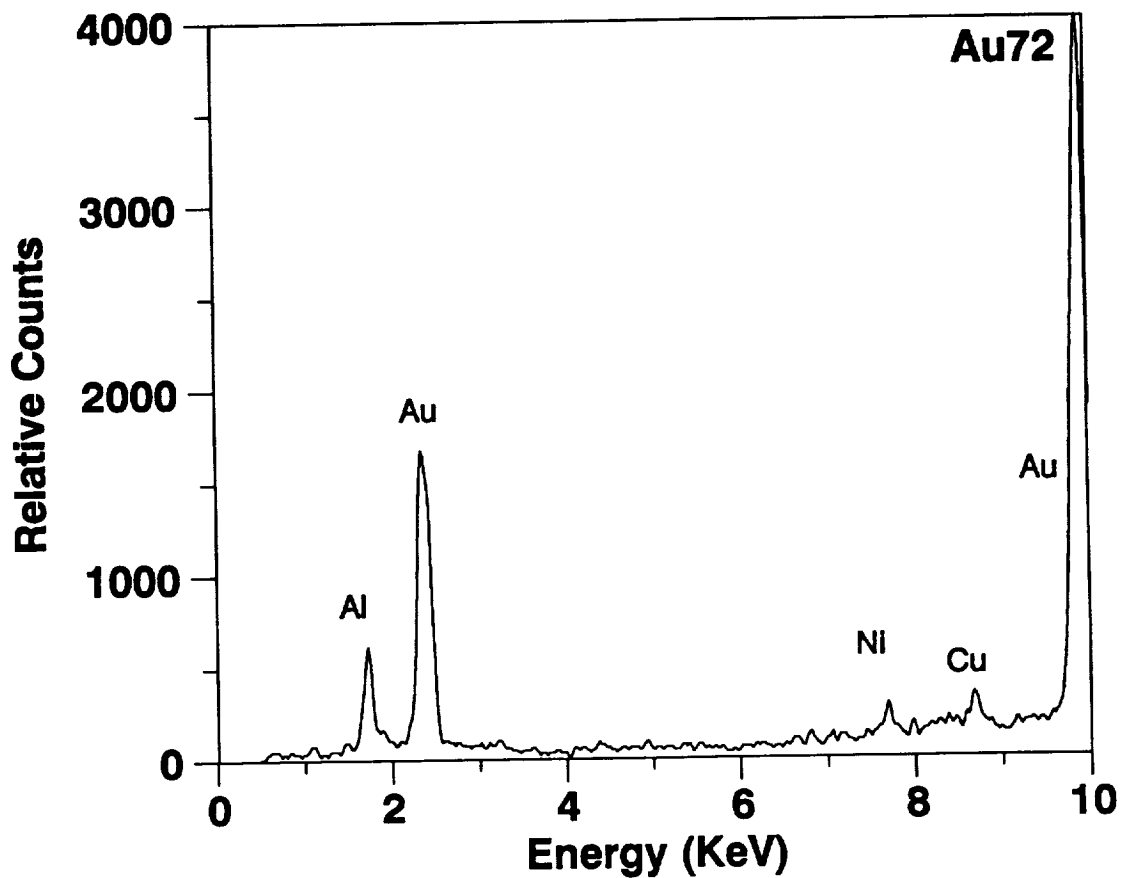
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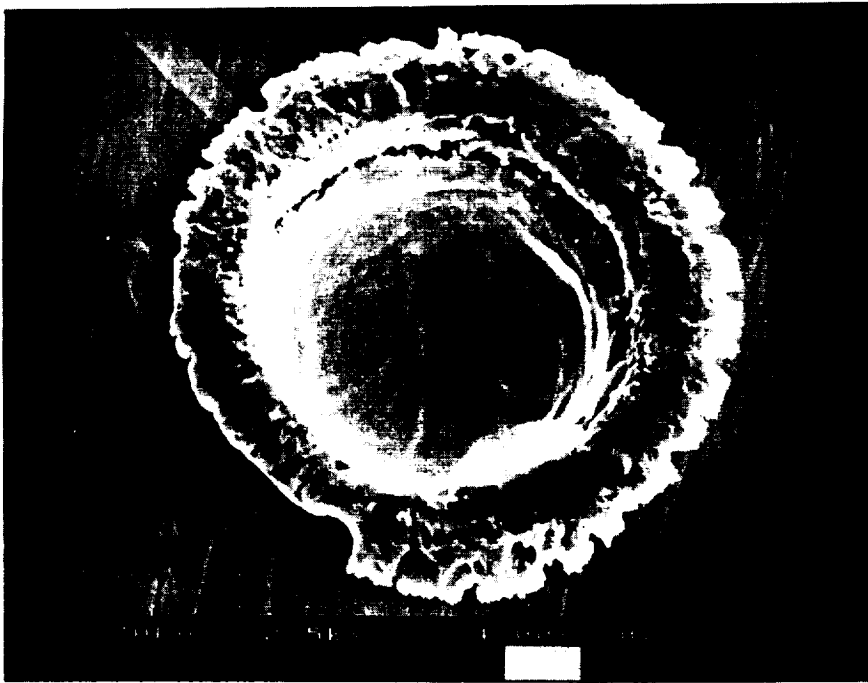
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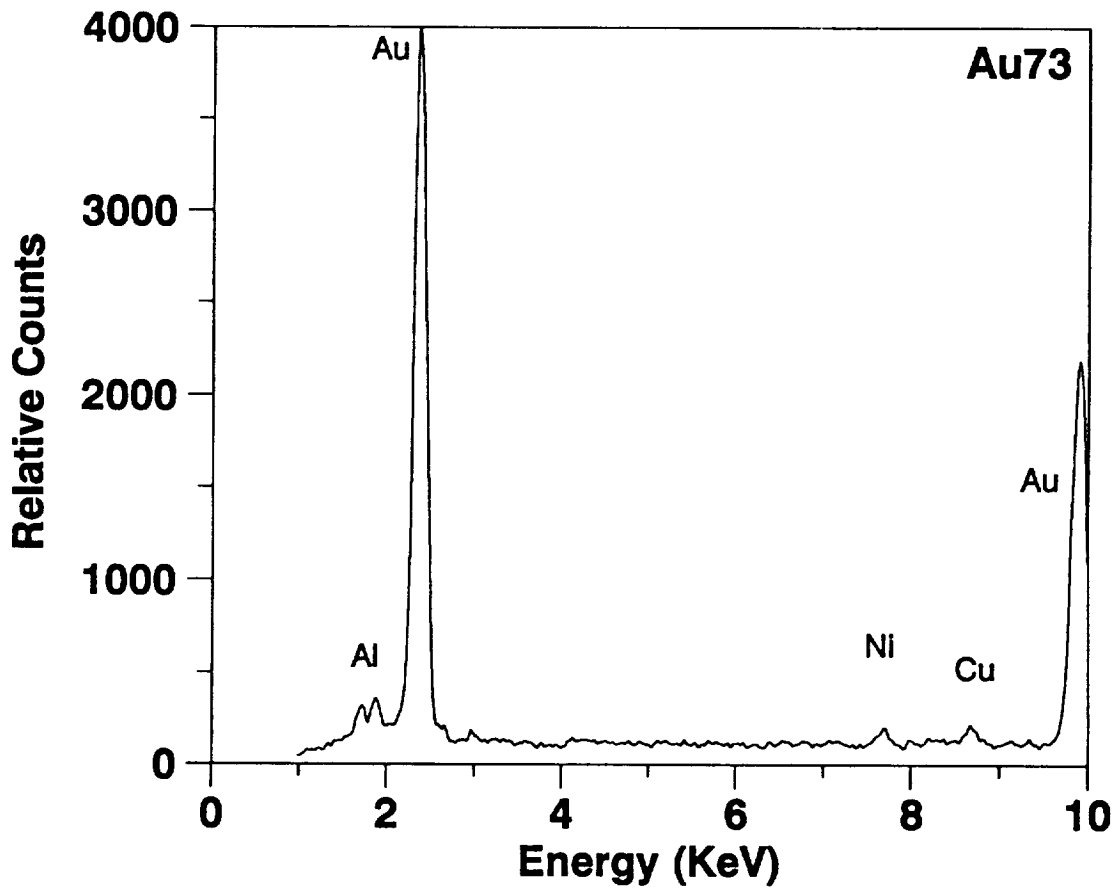


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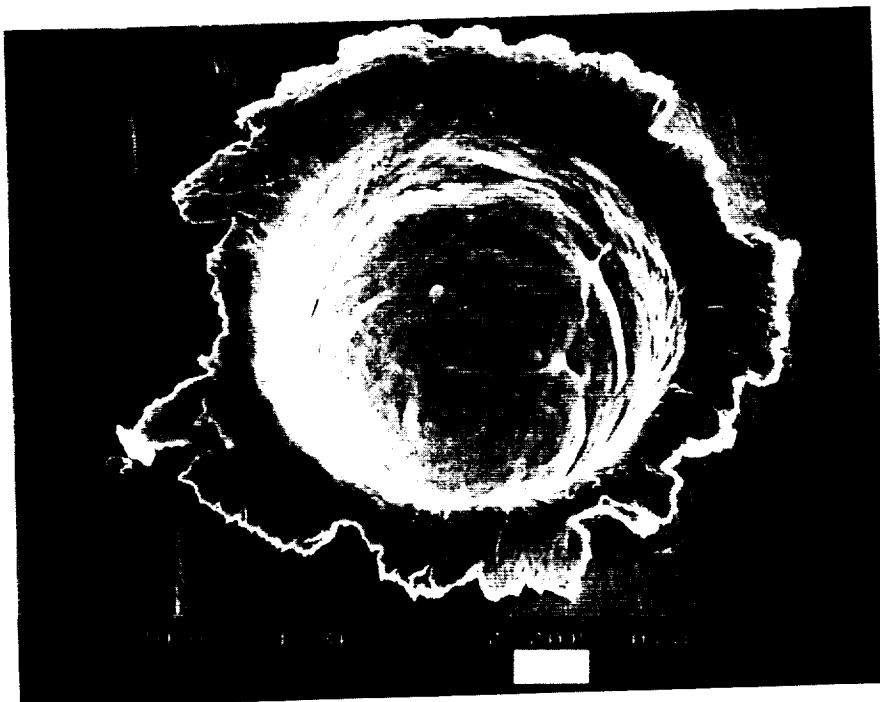


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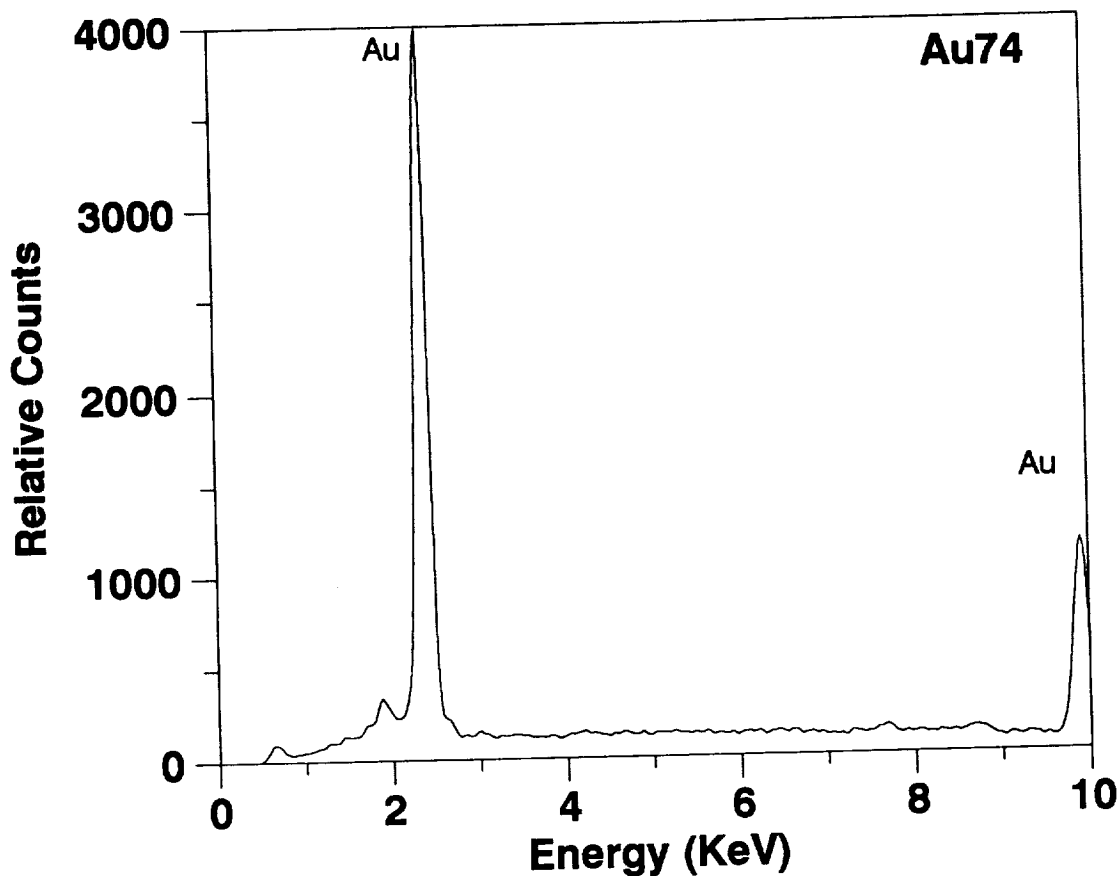


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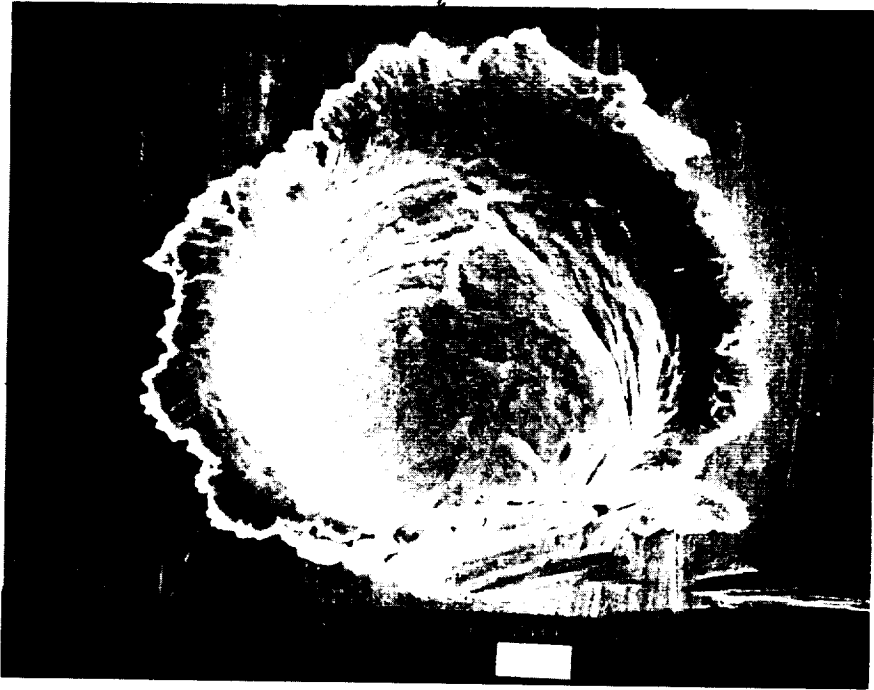


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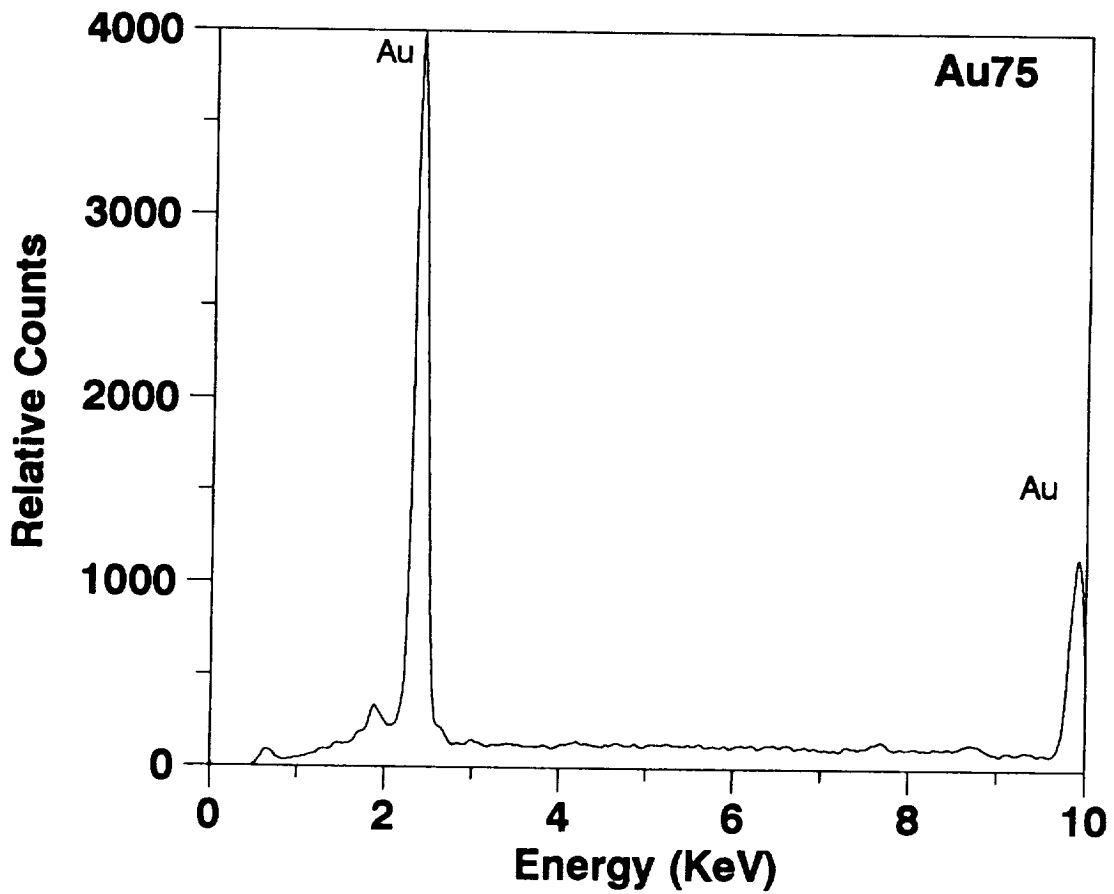
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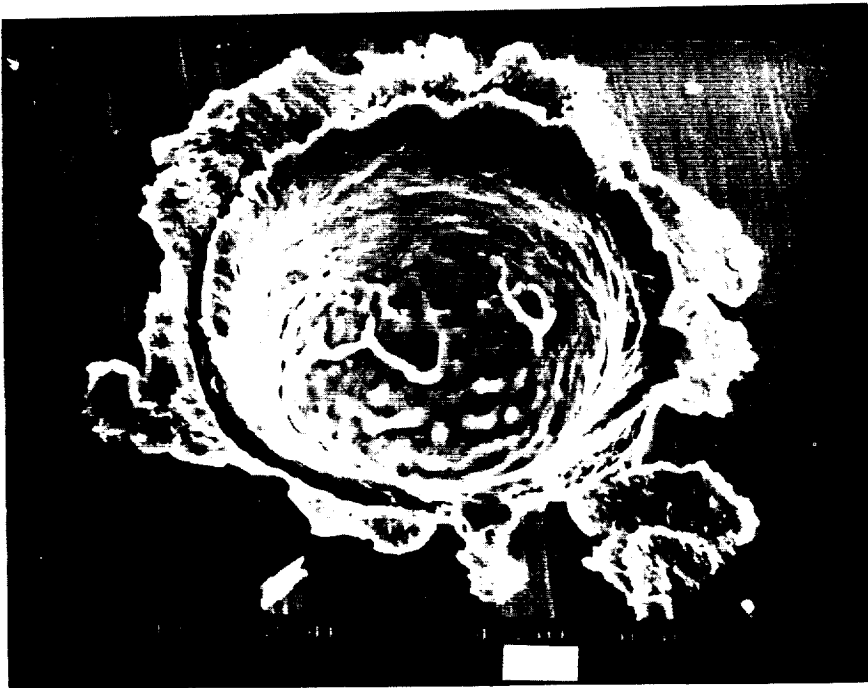
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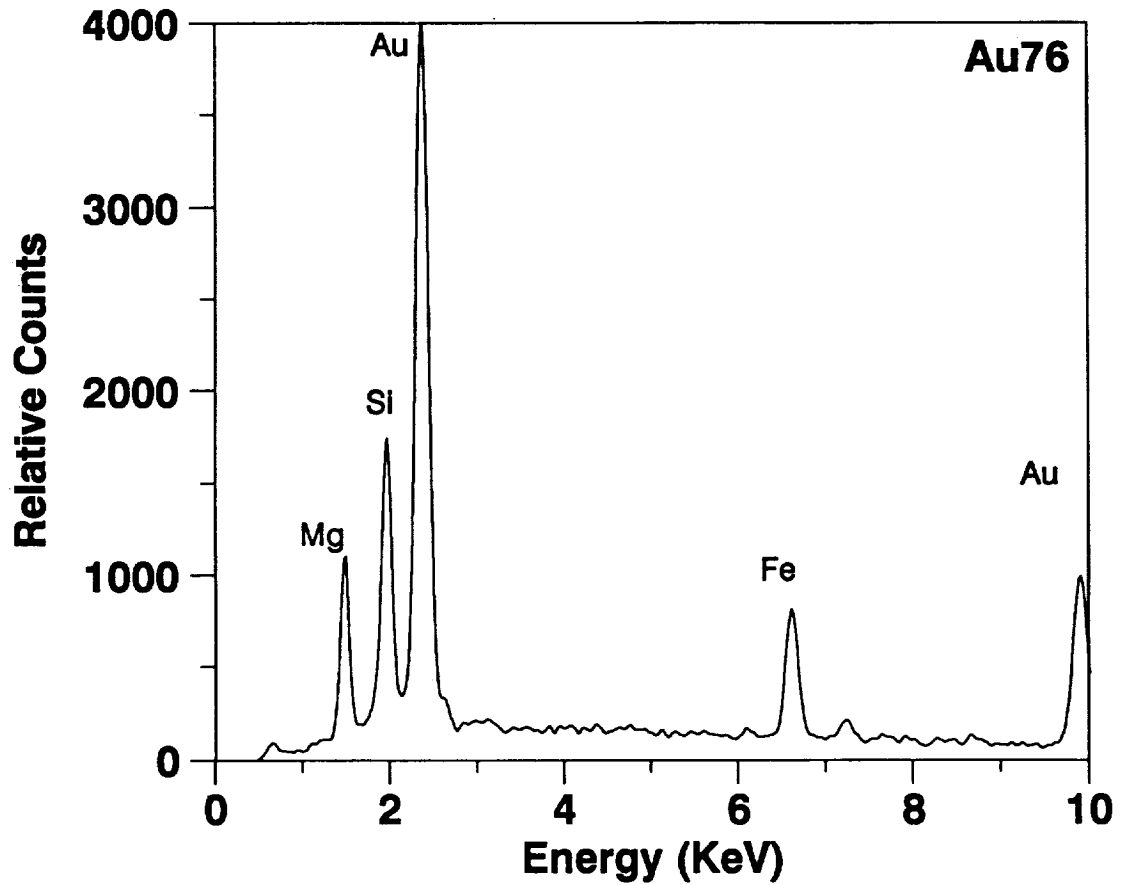


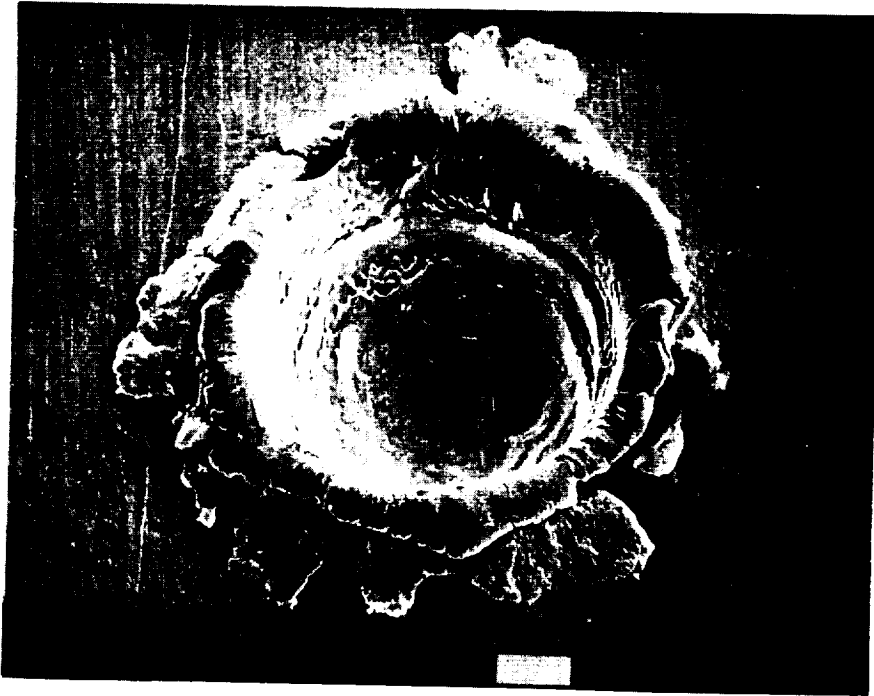
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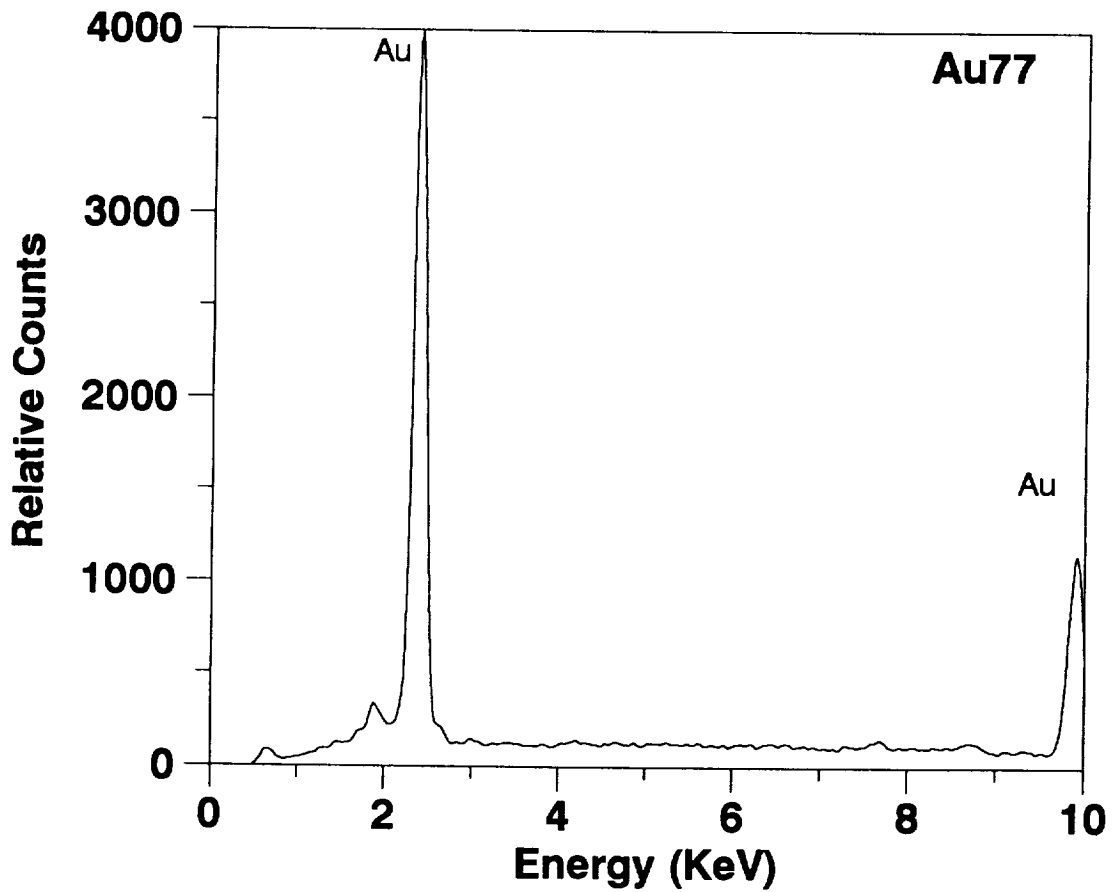


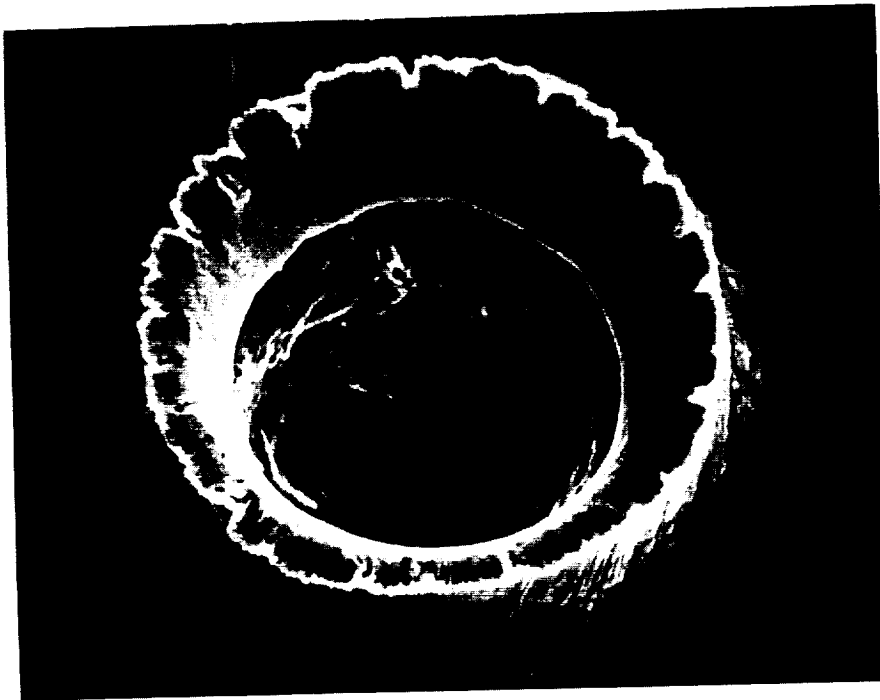
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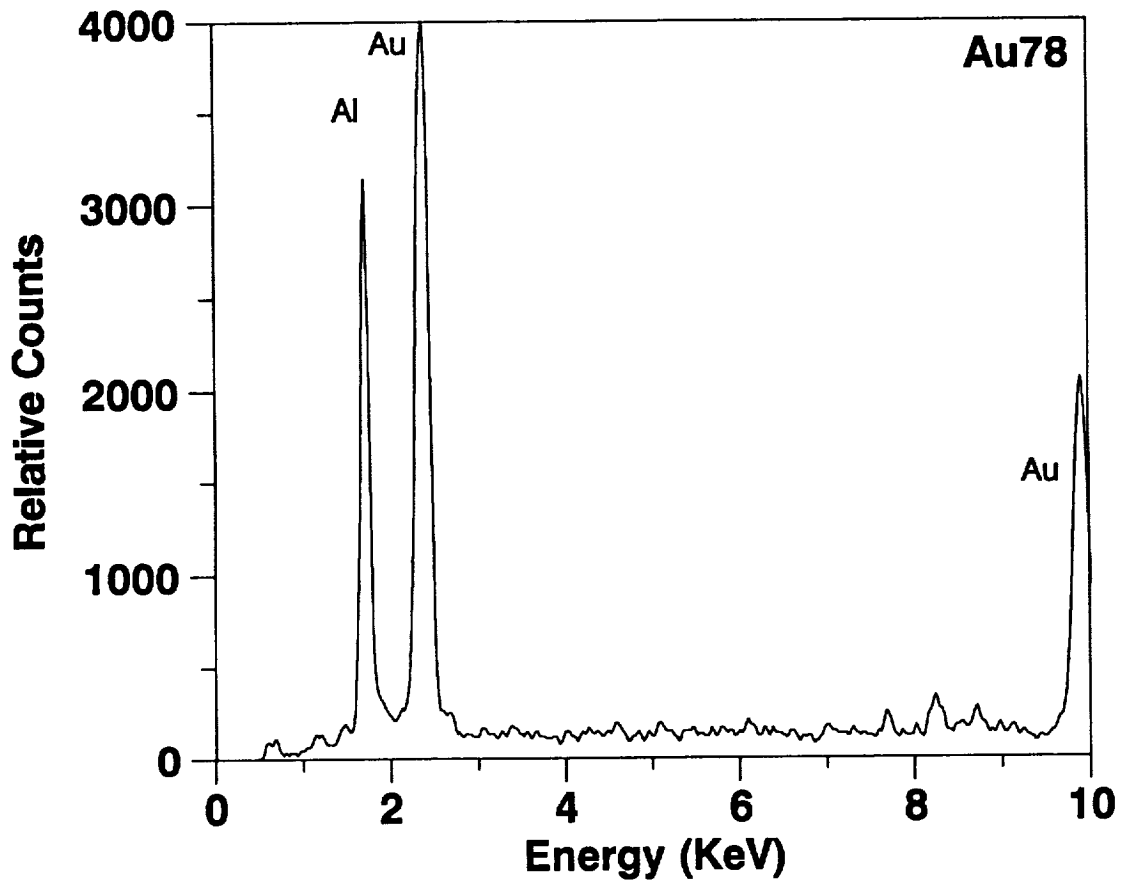


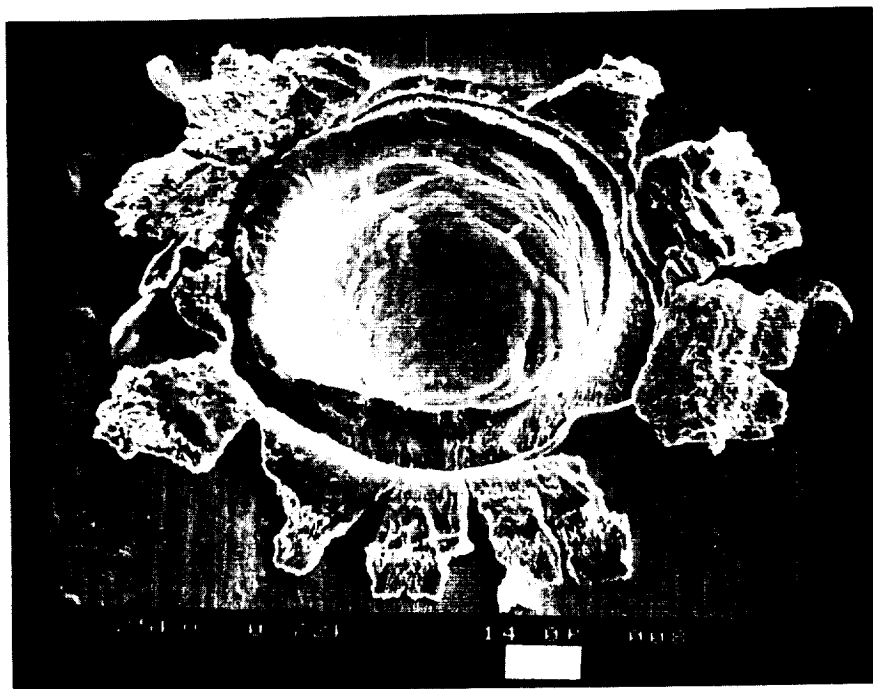
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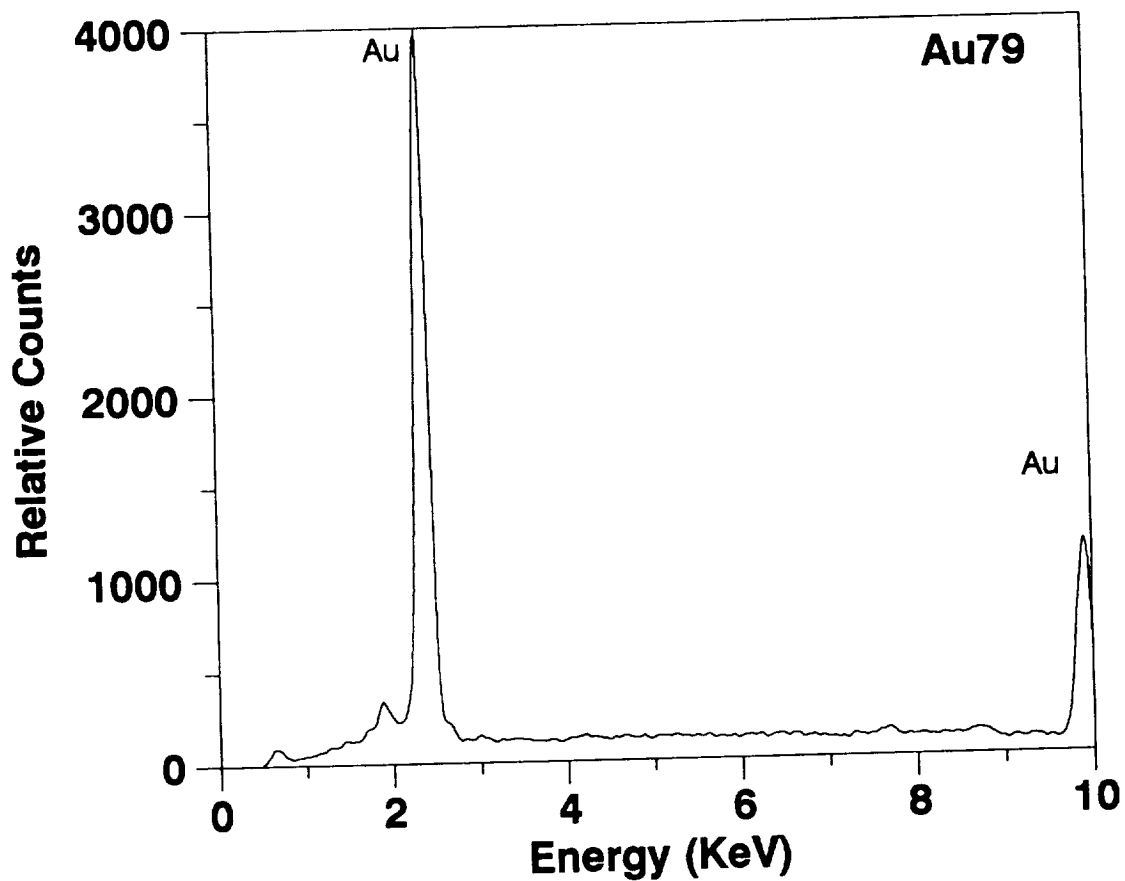


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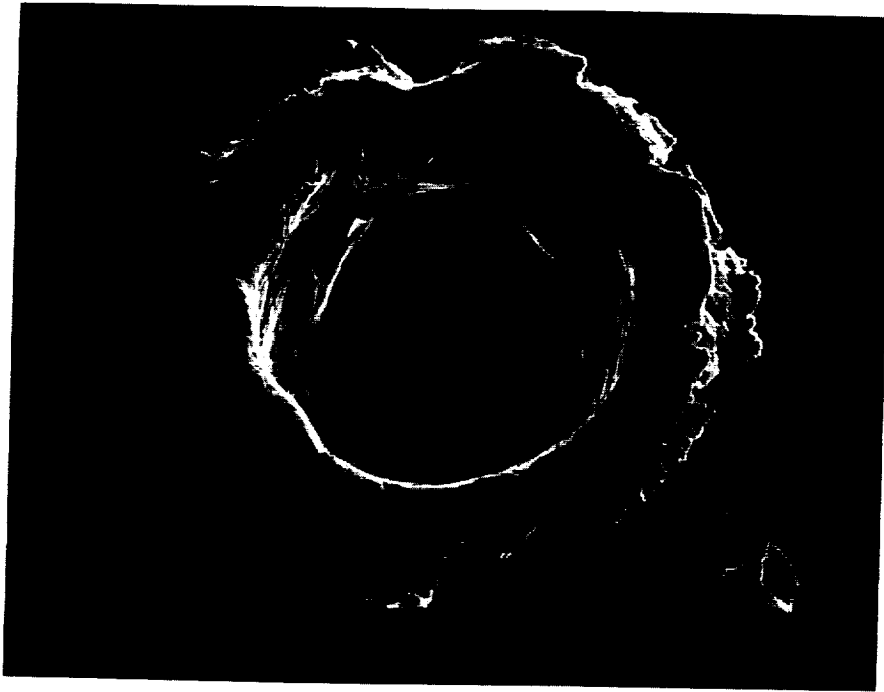


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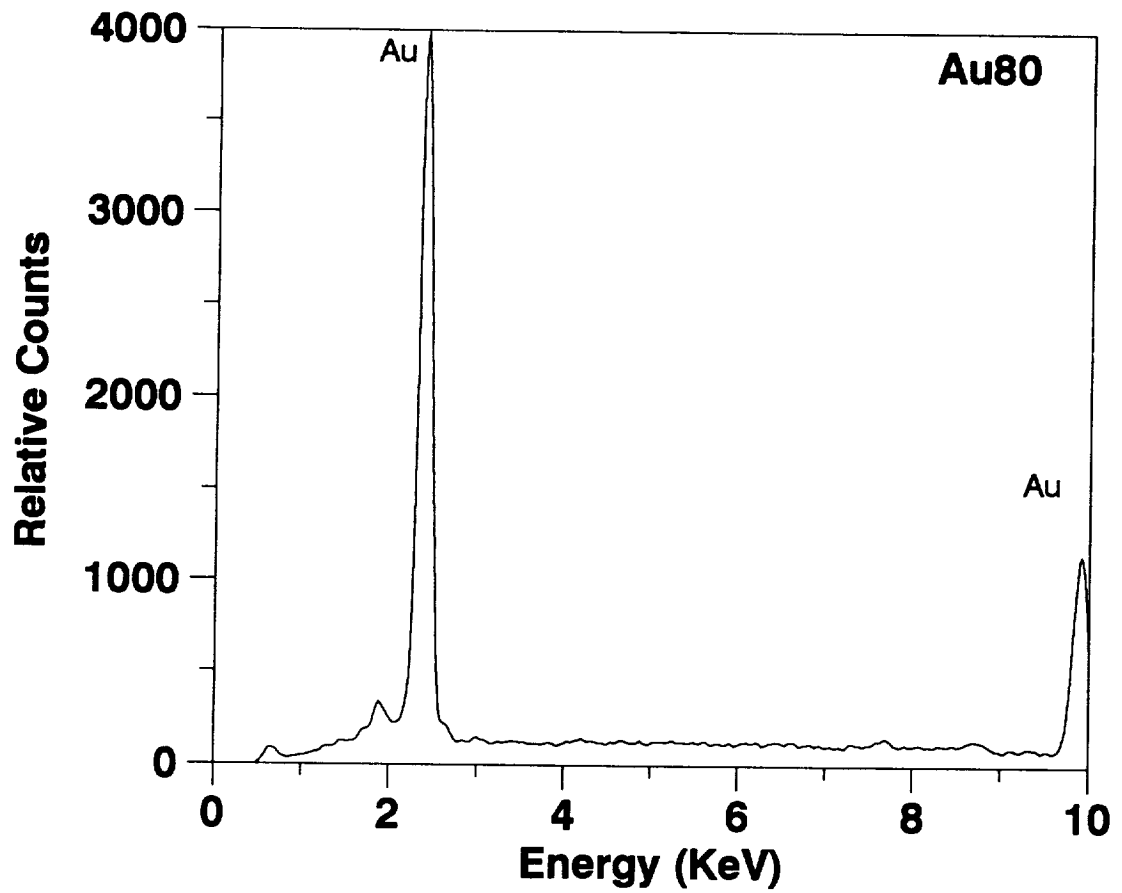


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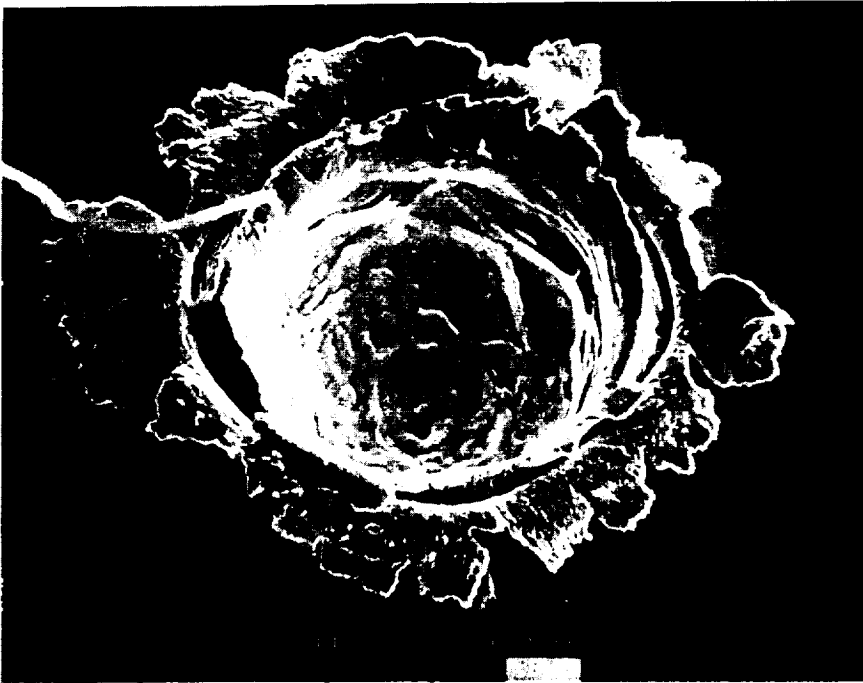


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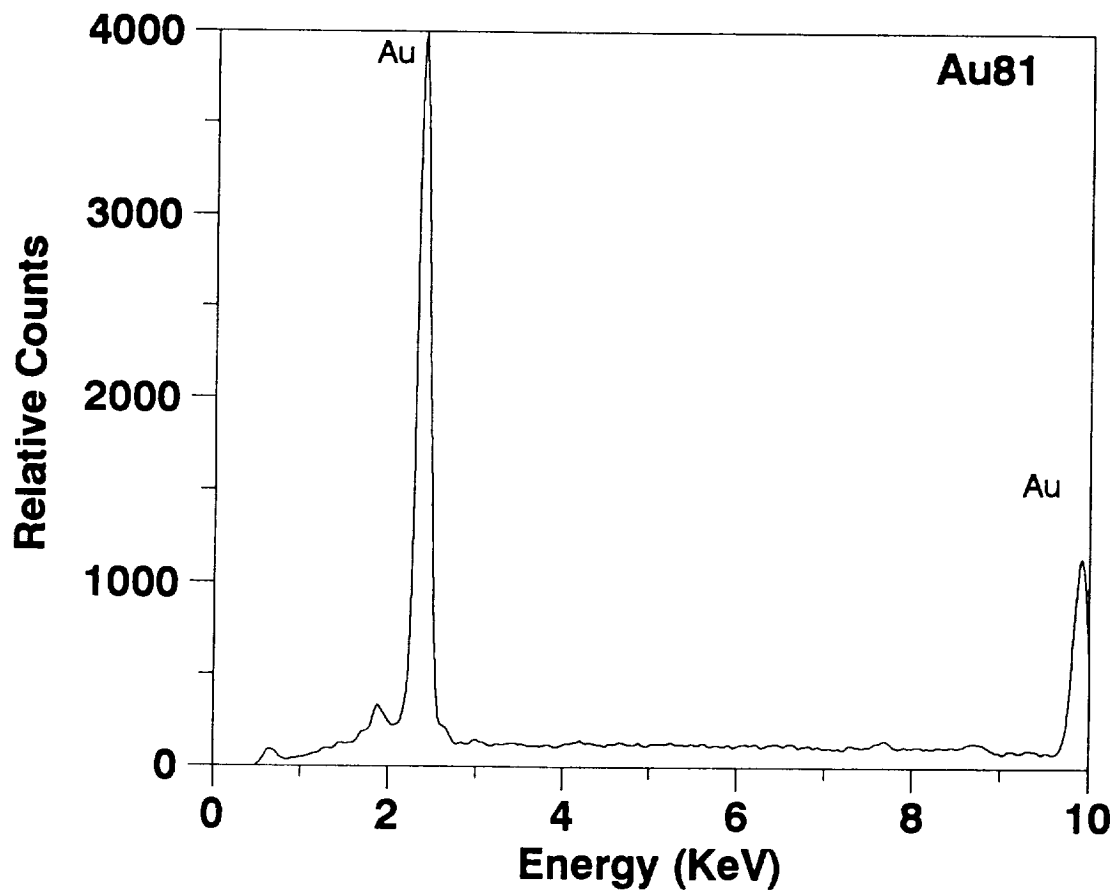
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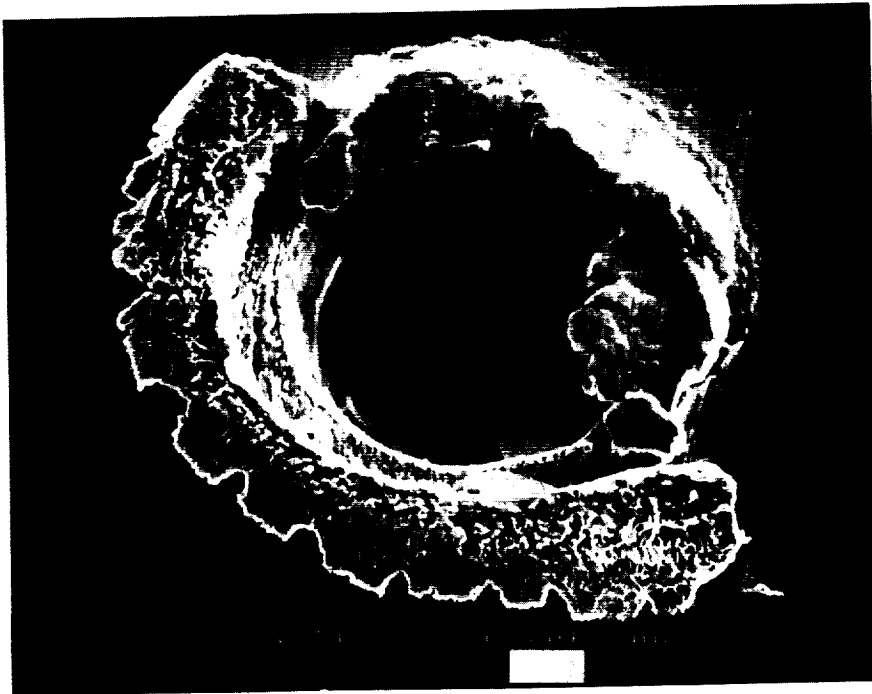
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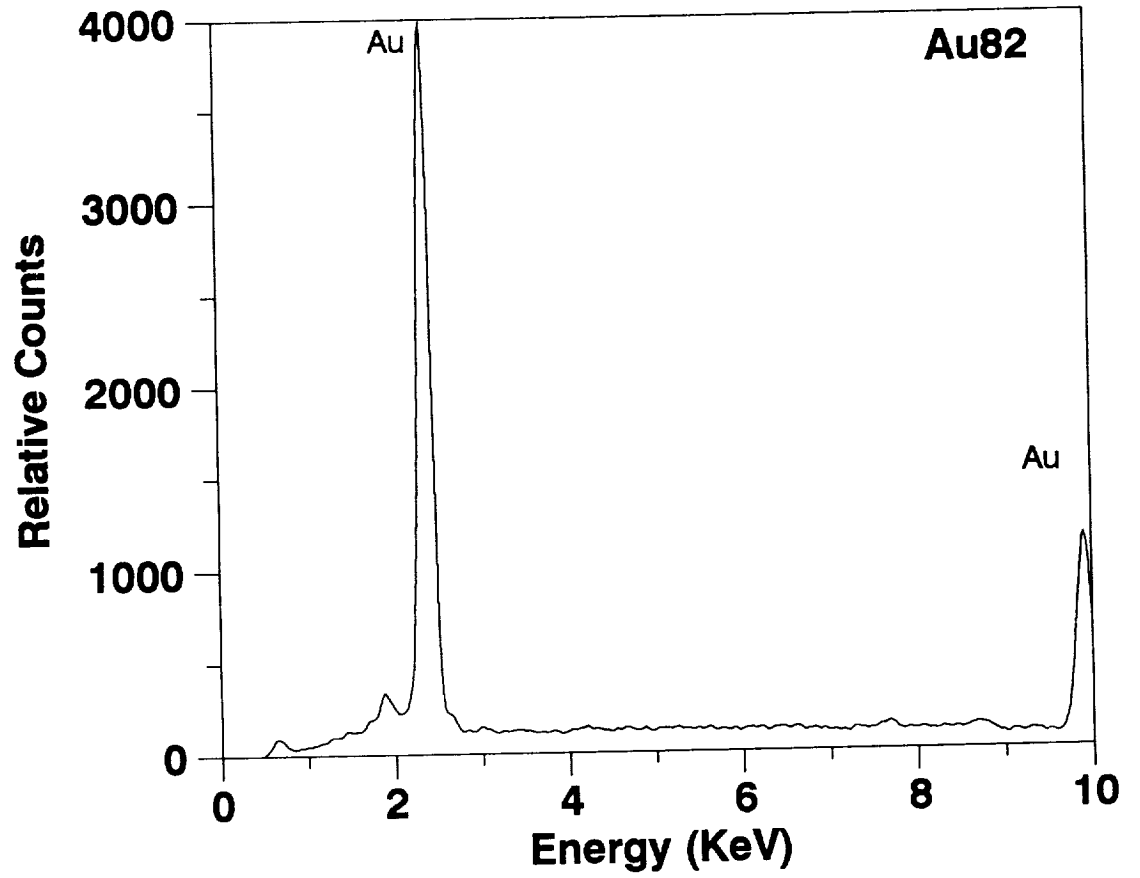


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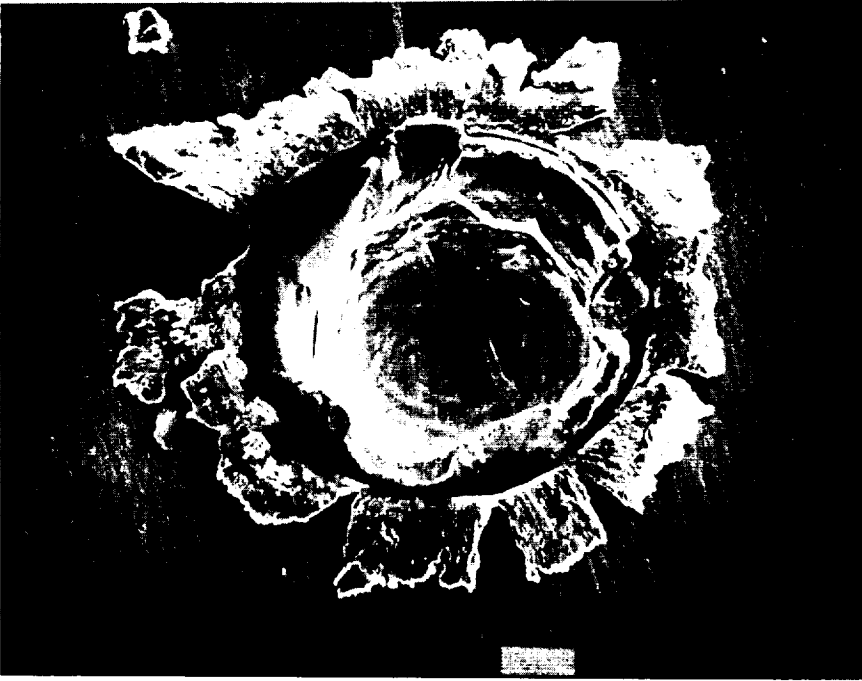


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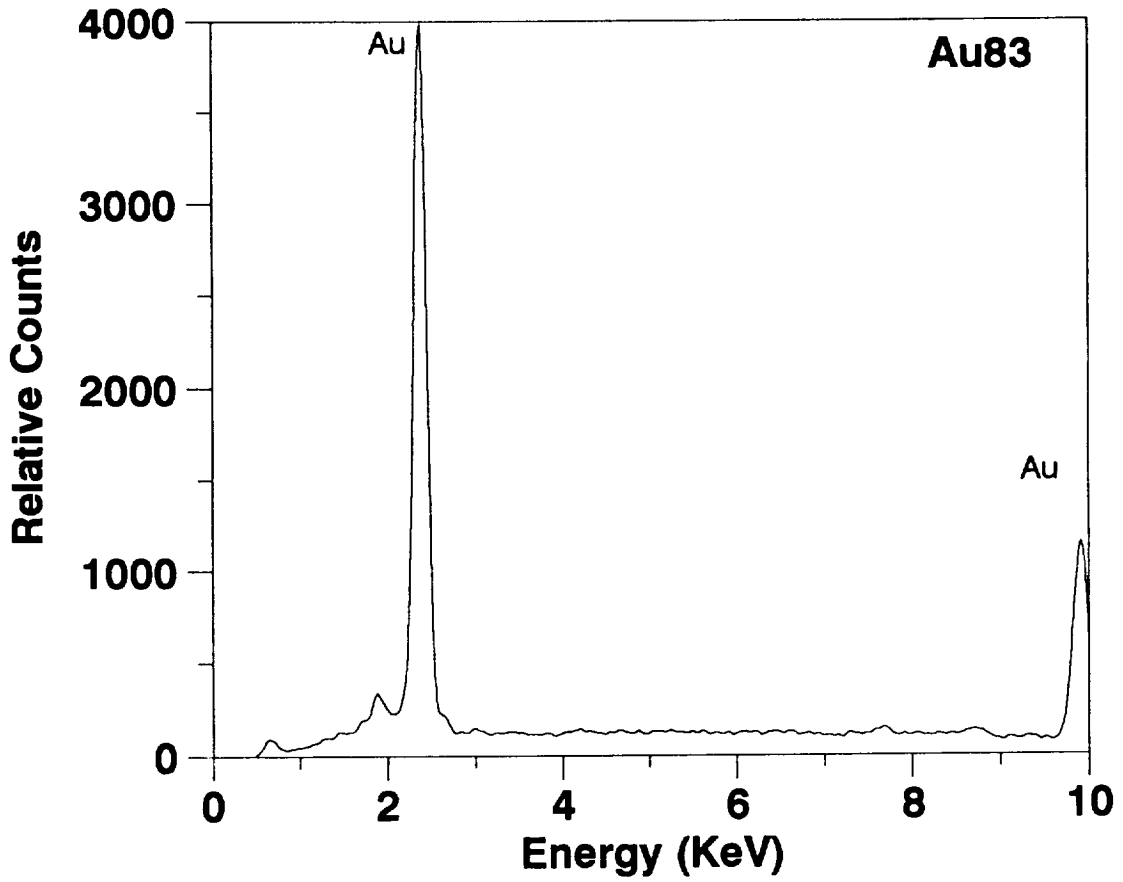
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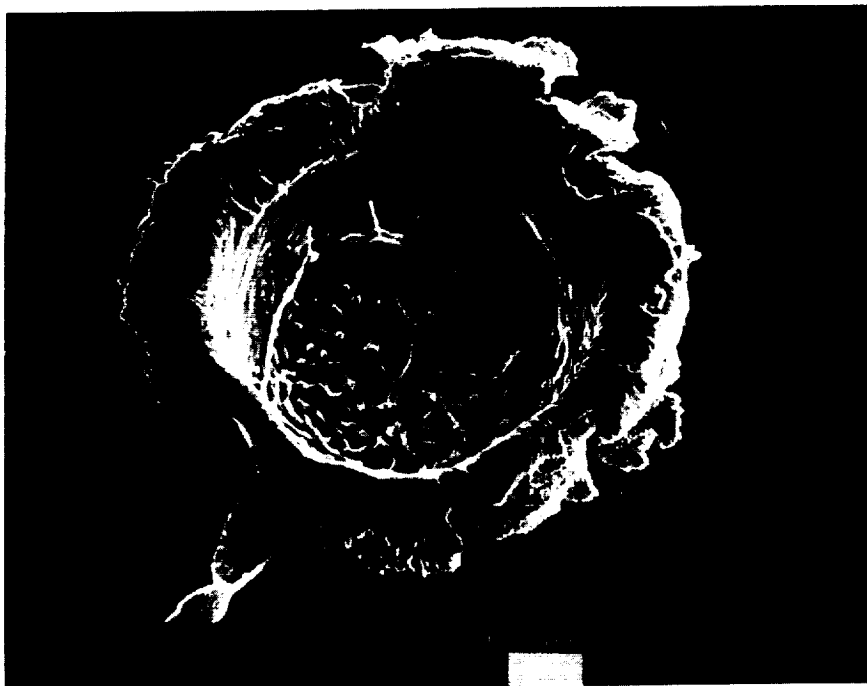
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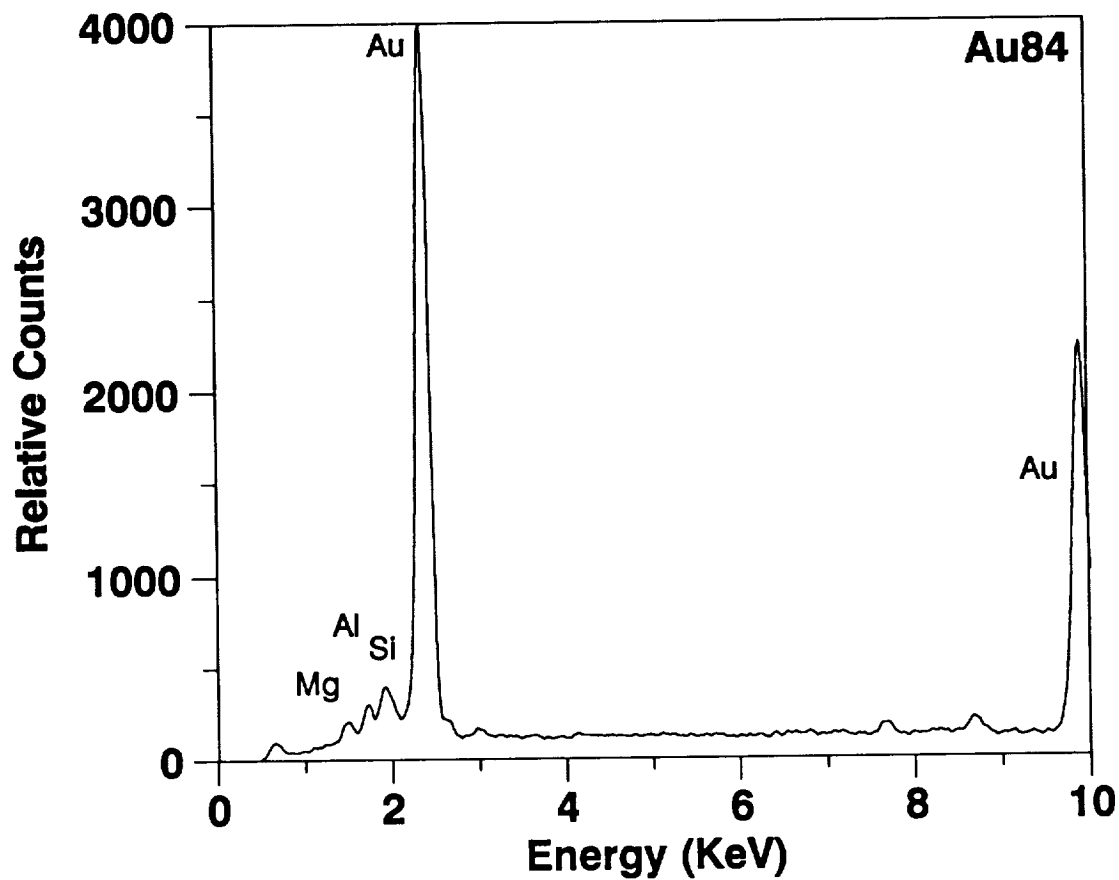
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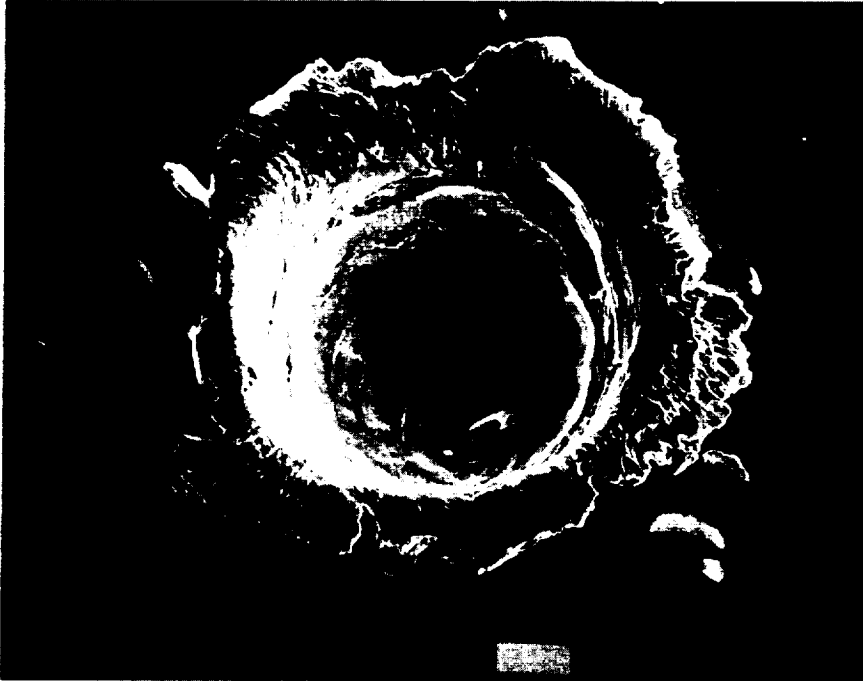
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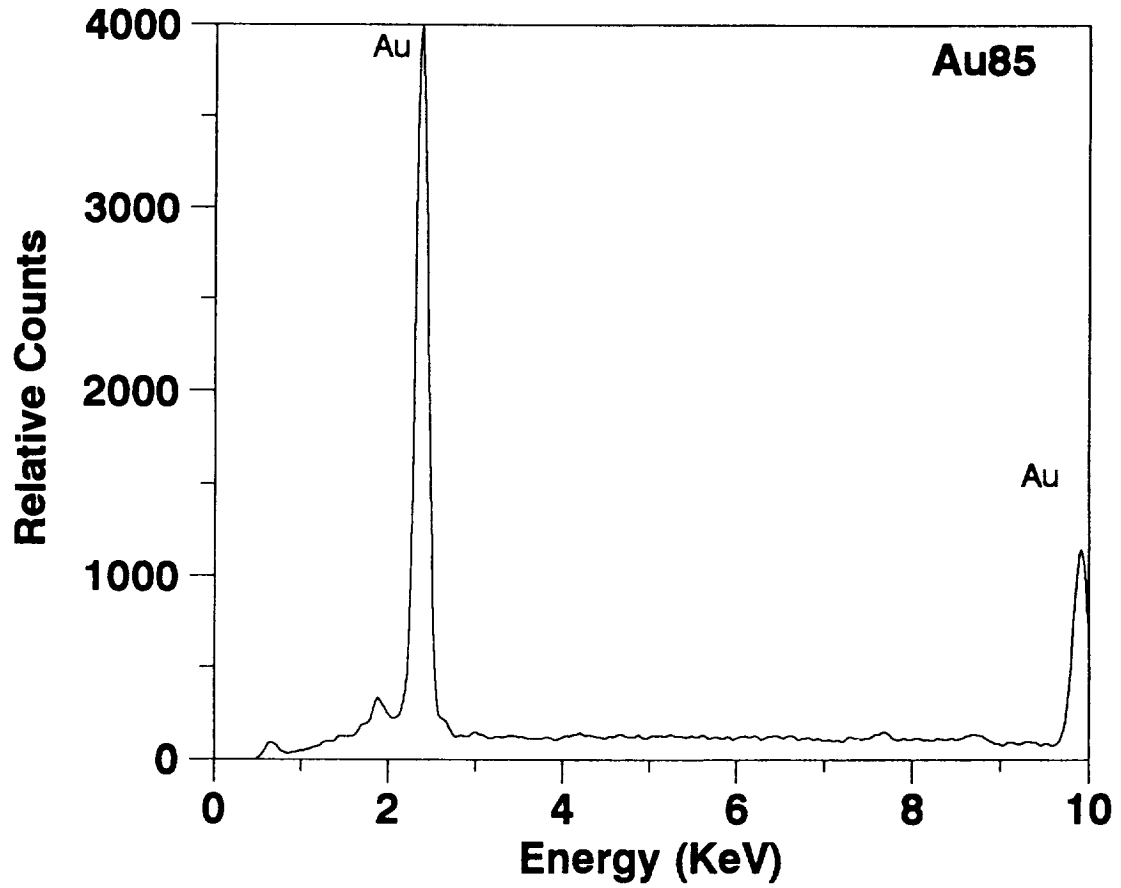


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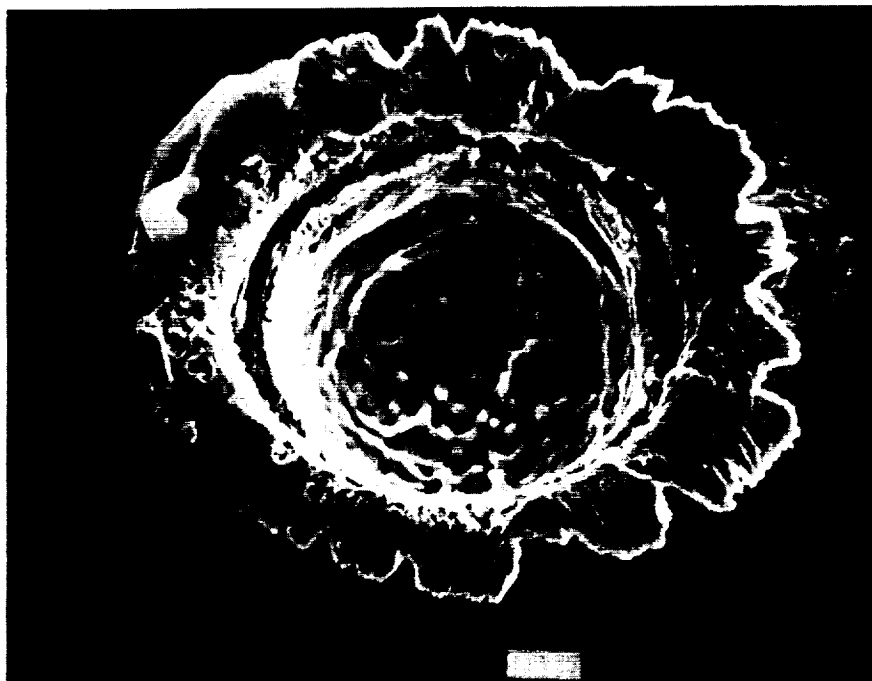


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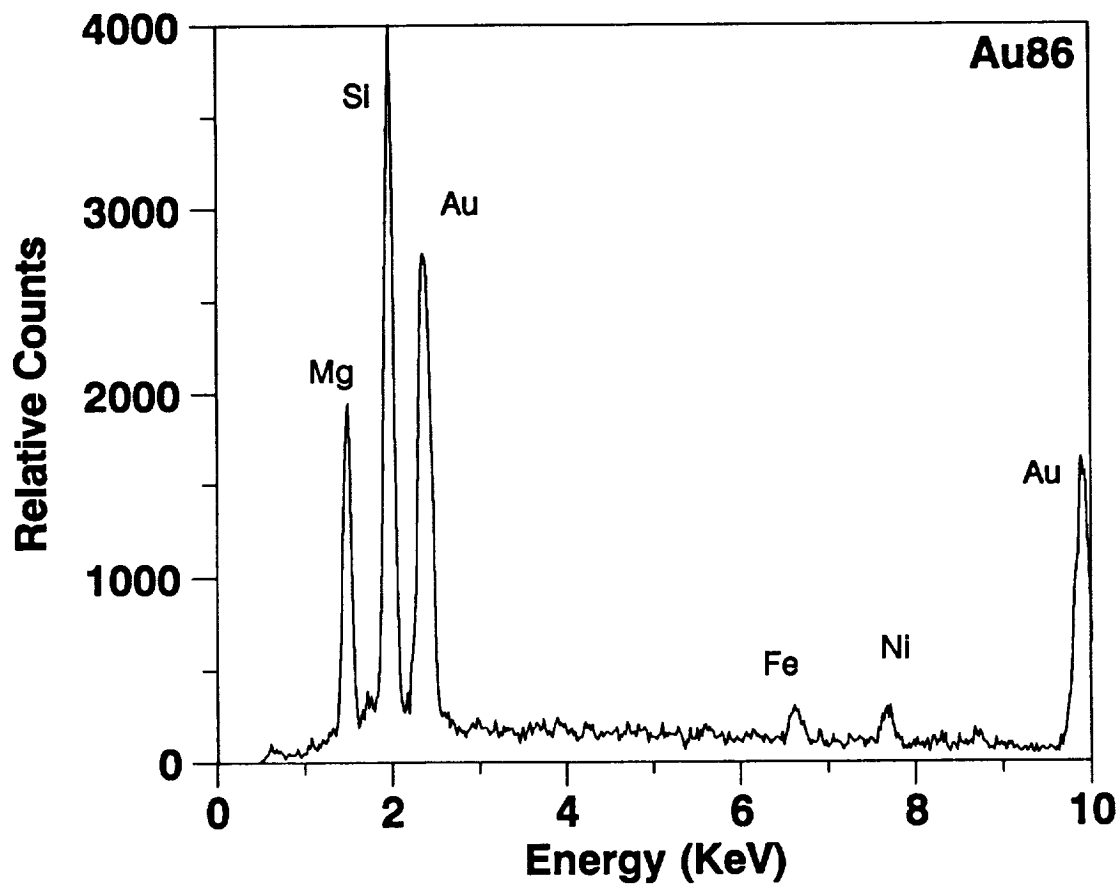
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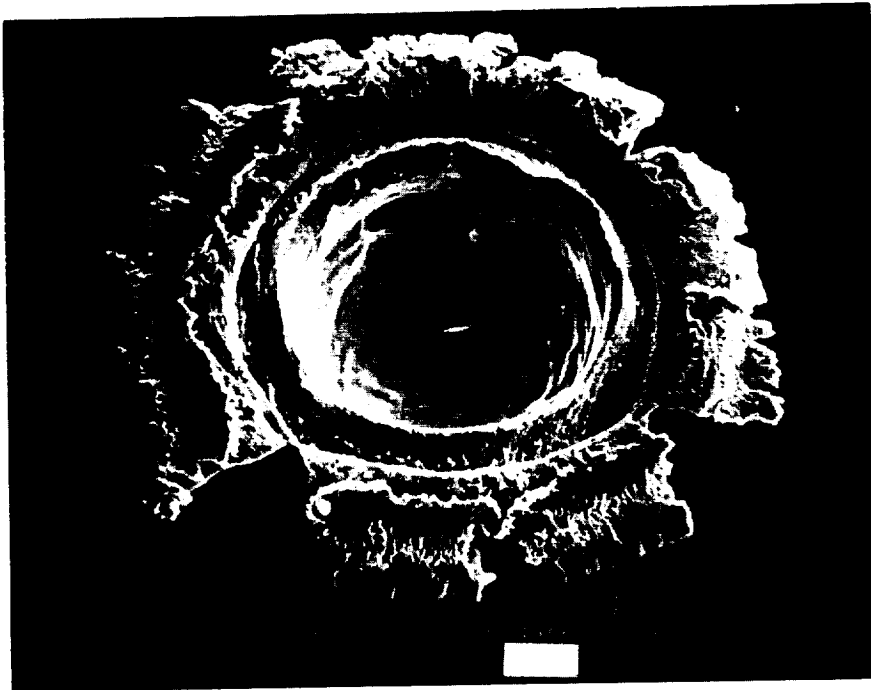
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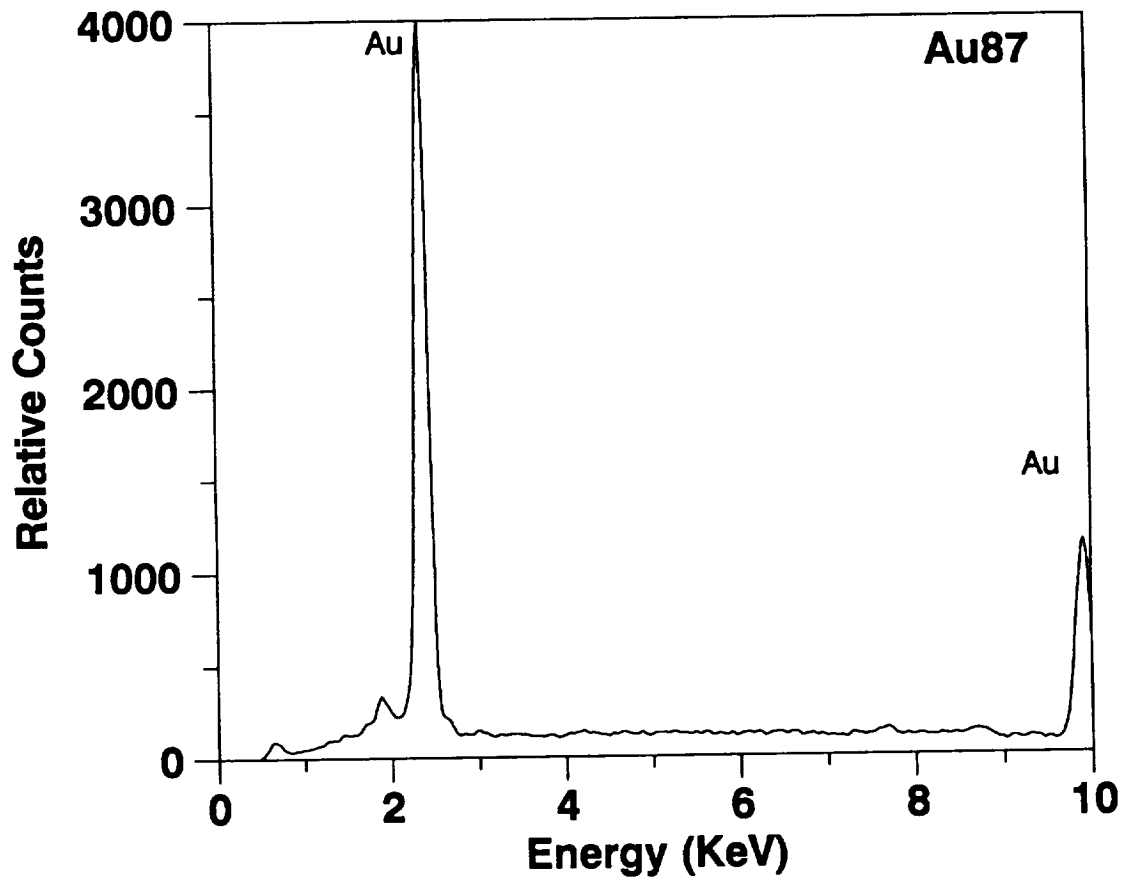


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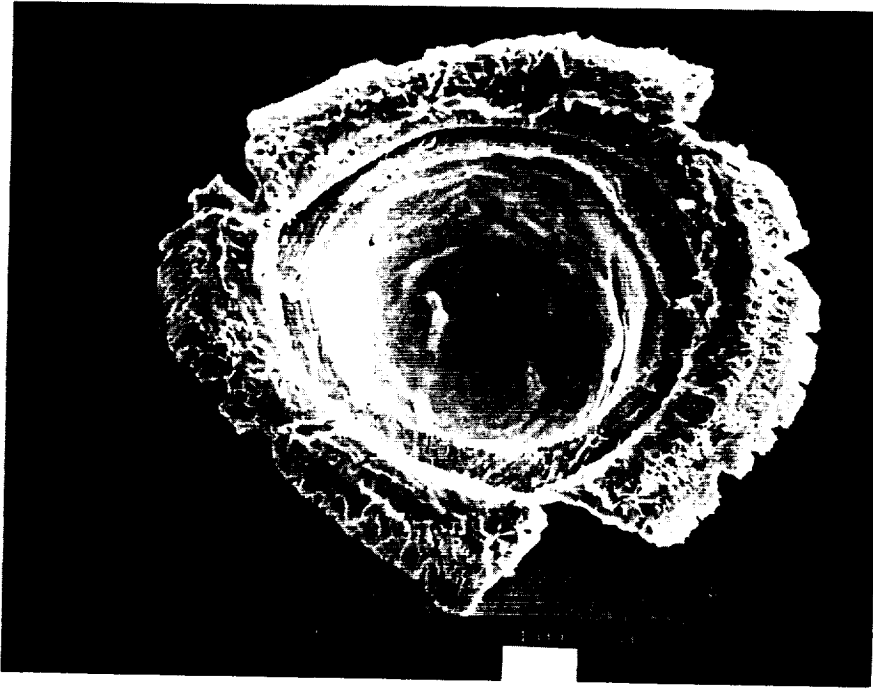


COMPONENT: EOOE
FEATURE: 87
CORE: LD-21
DIAMETER: 60 μ m
ORIGIN: Unknown

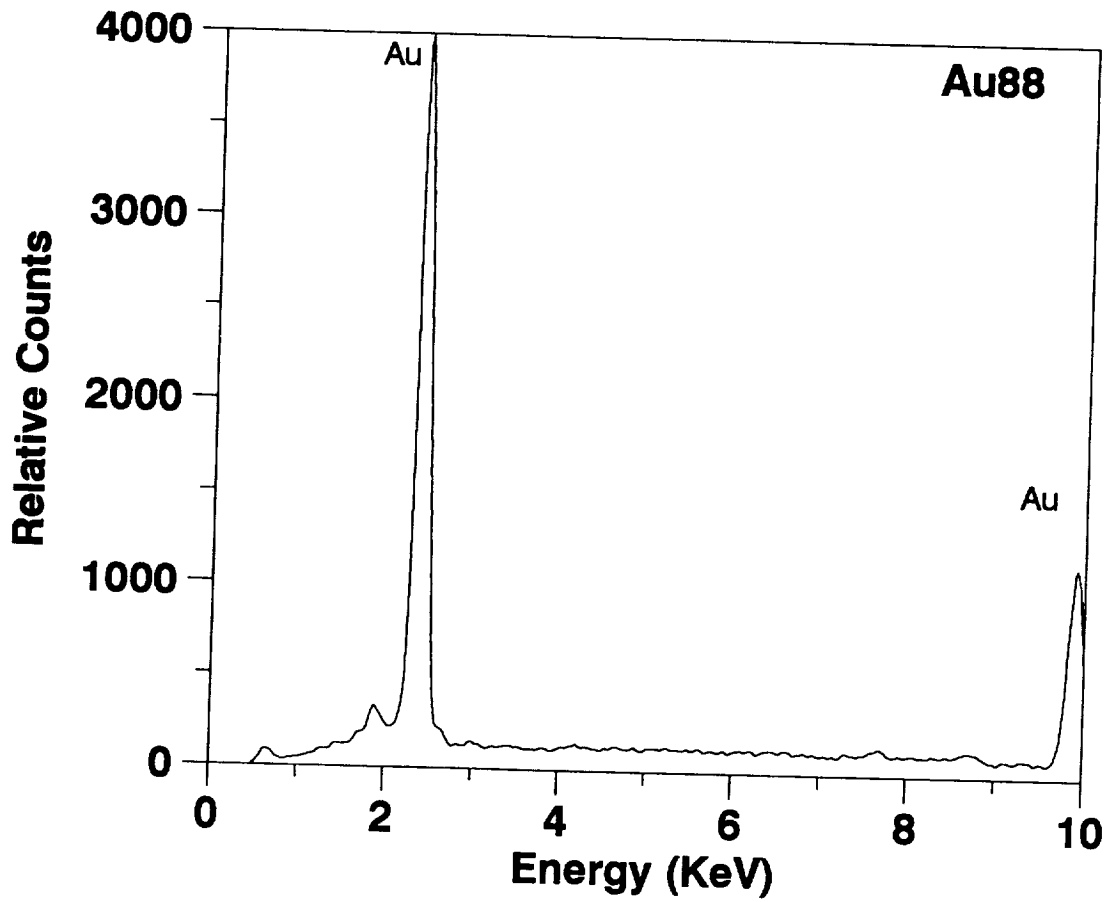


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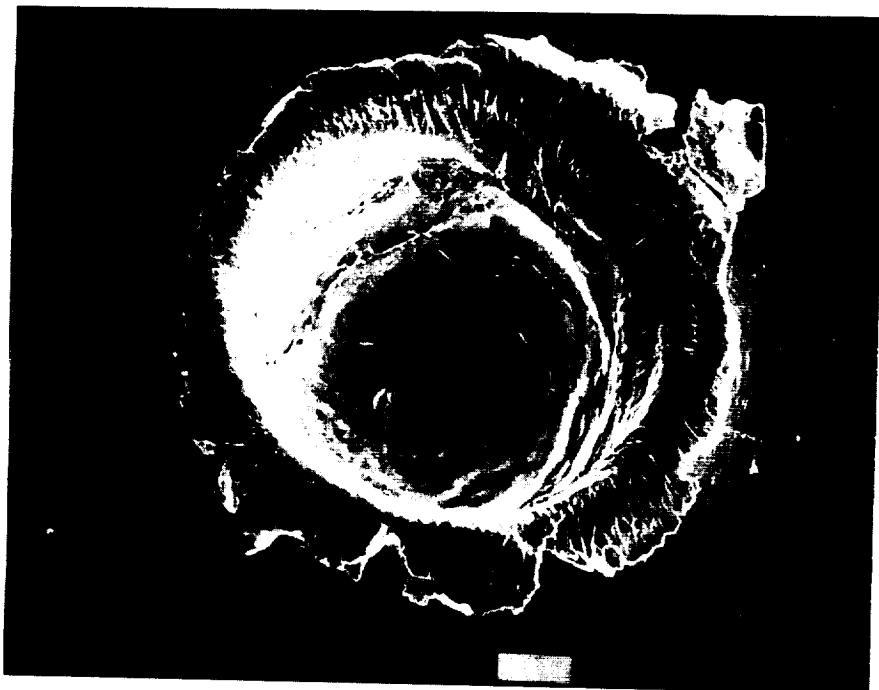


COMPONENT: EOOE
FEATURE: 88
CORE: LD-20
DIAMETER: 40 μ m
ORIGIN: Unknown



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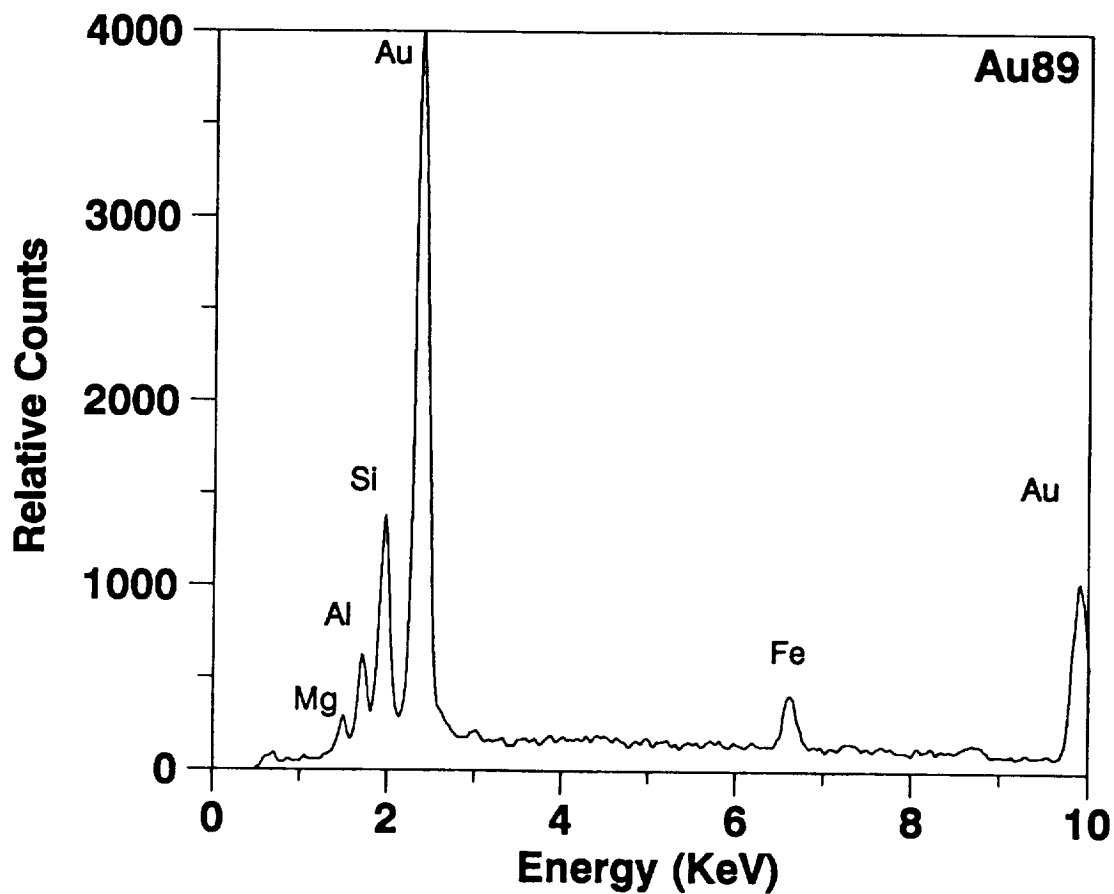
COMPONENT: EOOE

FEATURE: 89

CORE: LD-23

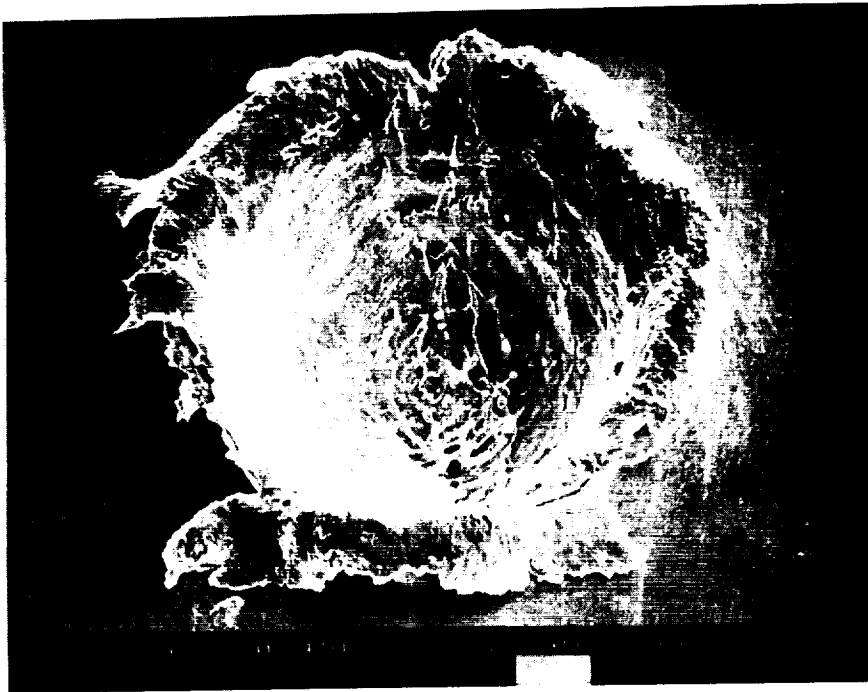
DIAMETER: 155 μ m

ORIGIN: Natural



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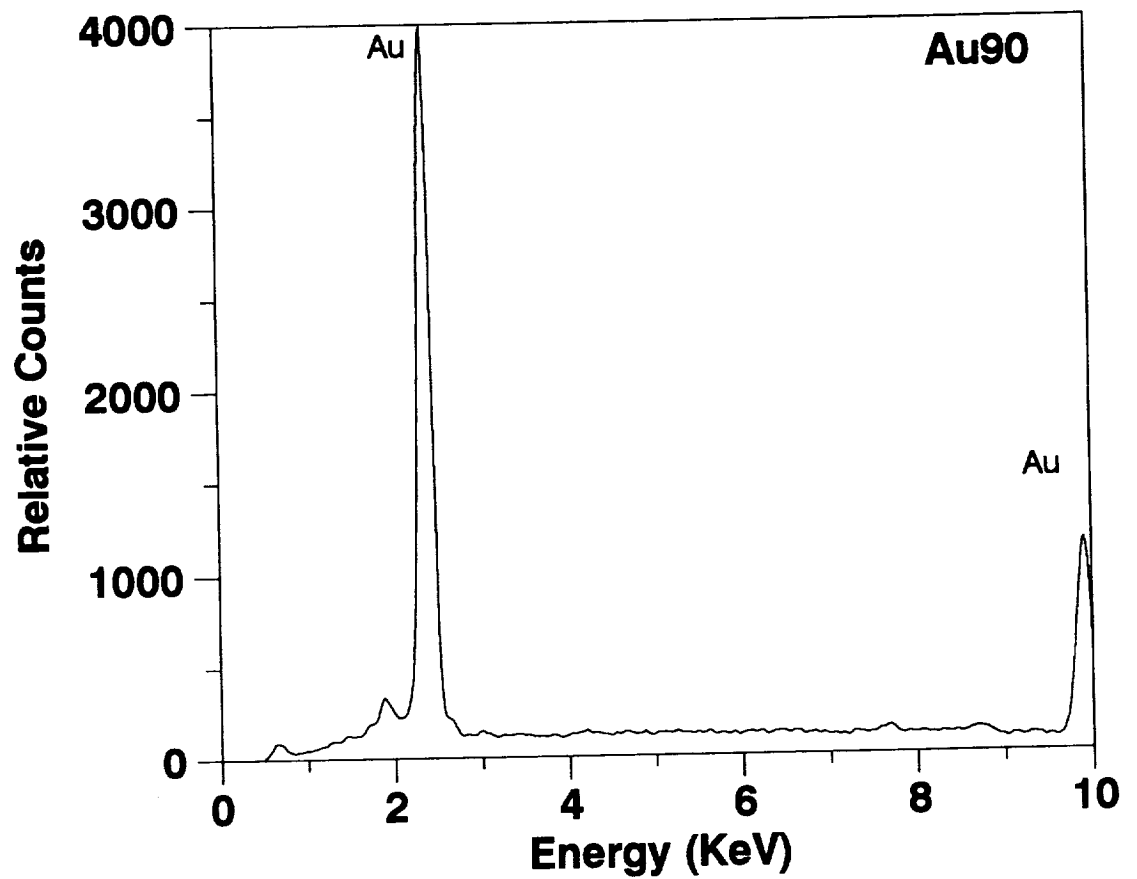
COMPONENT: EOOE

FEATURE: 90

CORE: LD-25

DIAMETER: 160 μm

ORIGIN: Unknown



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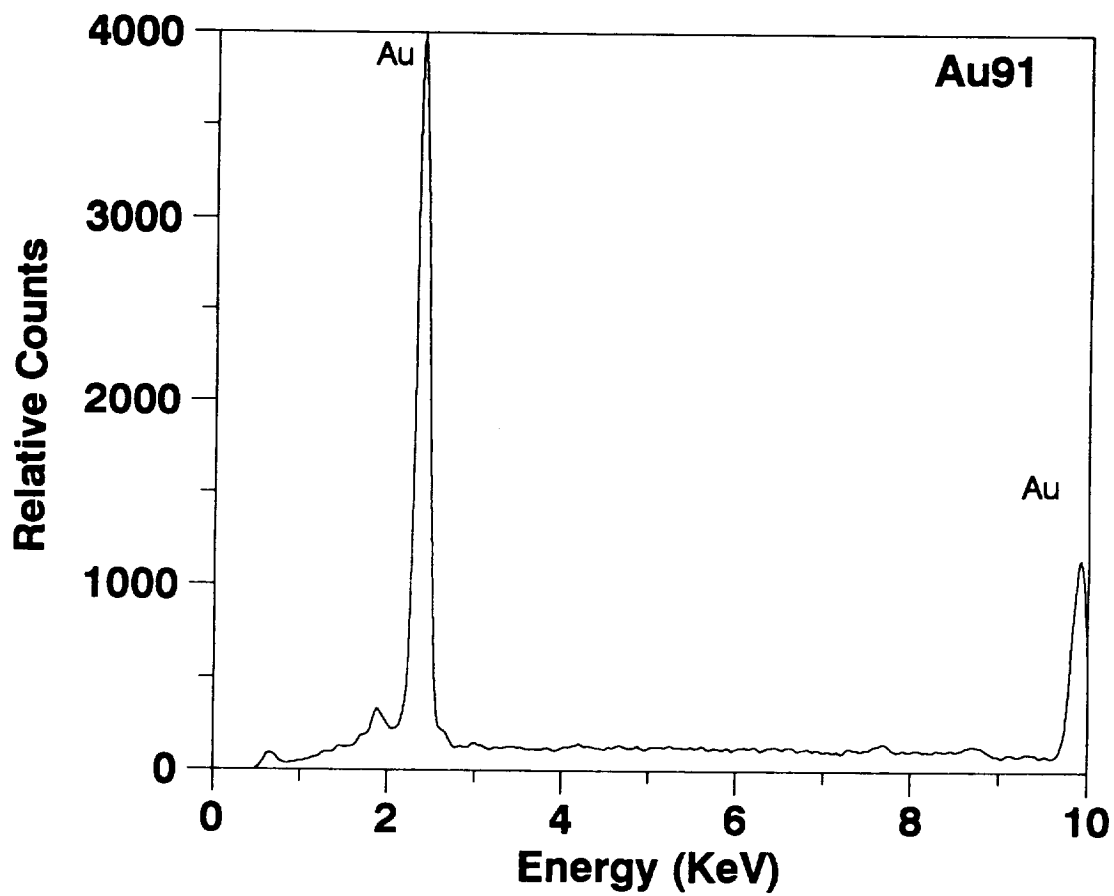
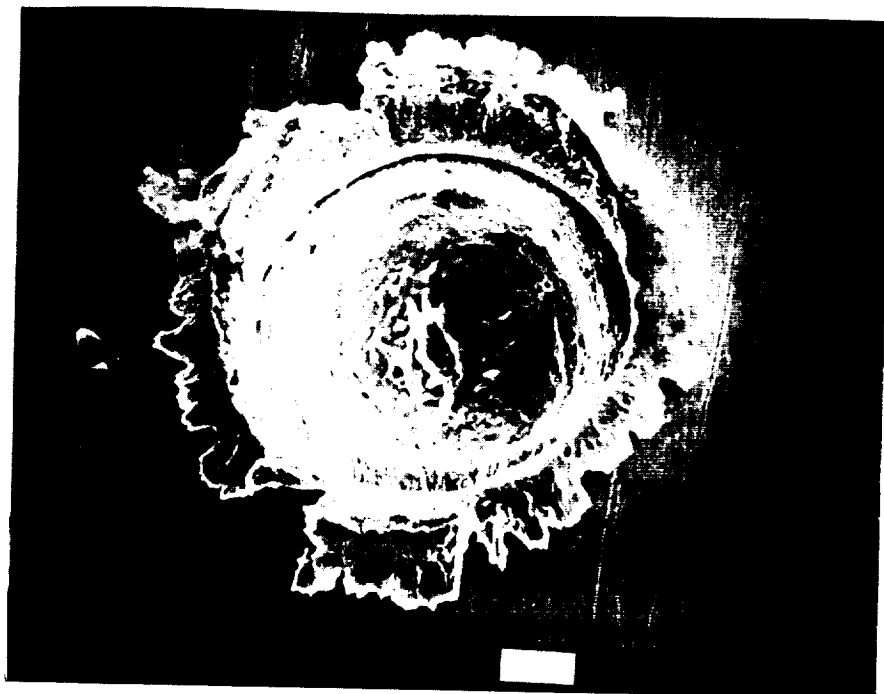
COMPONENT: EOOE

FEATURE: 91

CORE: LD-24

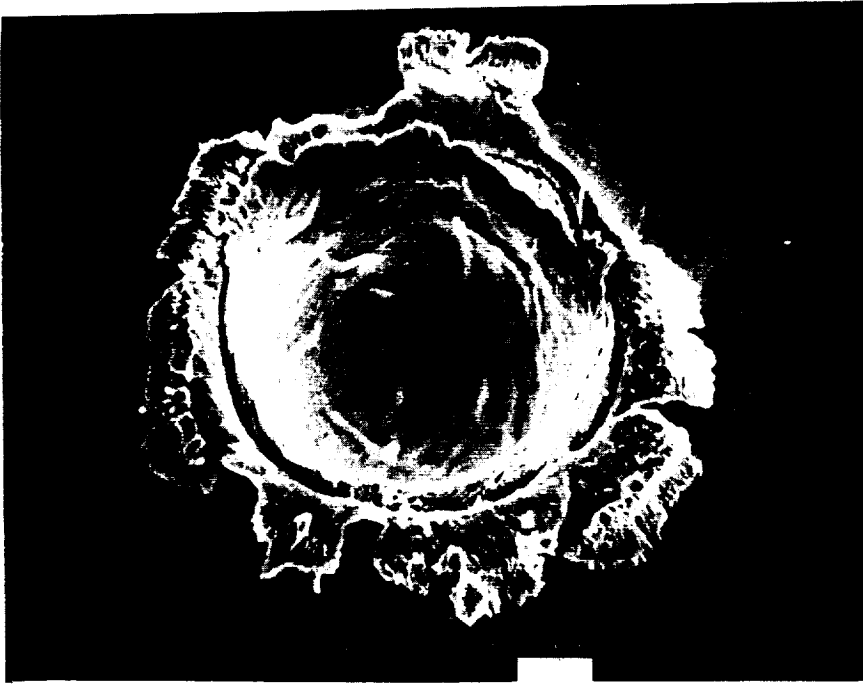
DIAMETER: 55 μm

ORIGIN: Unknown

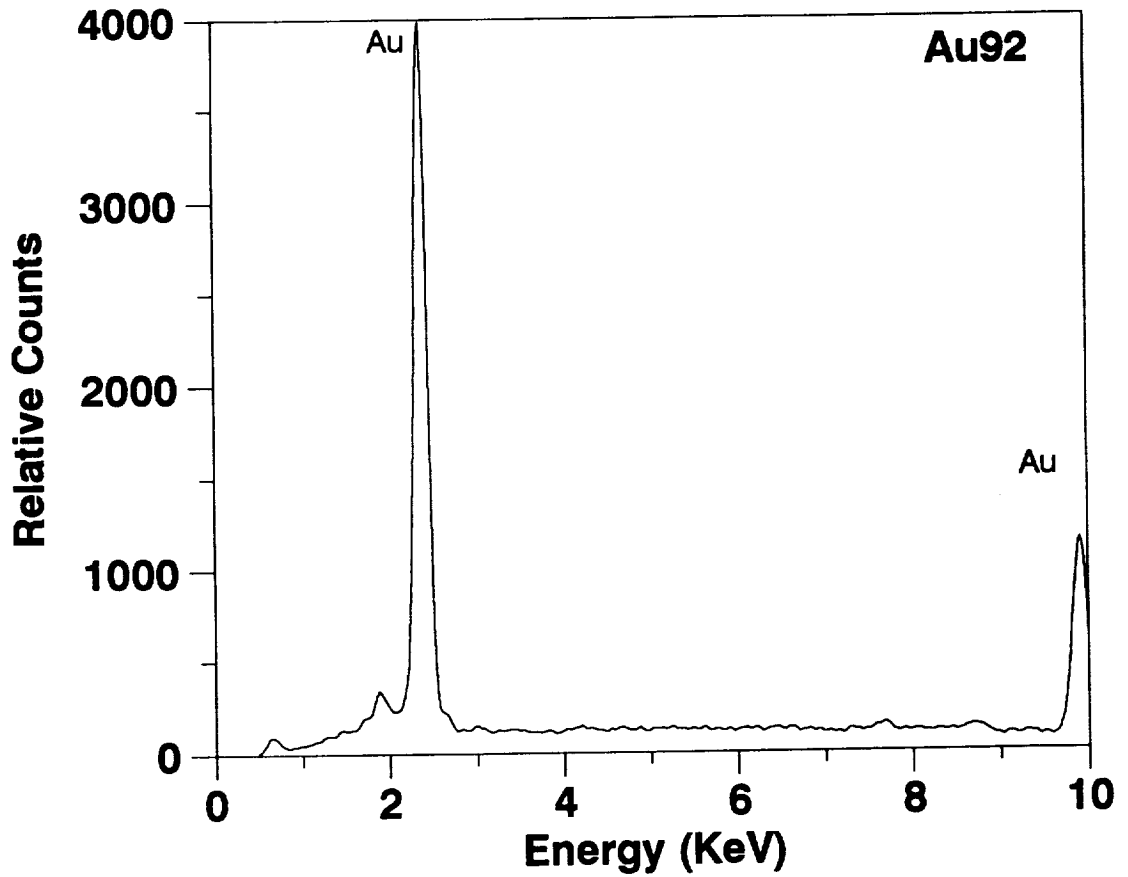


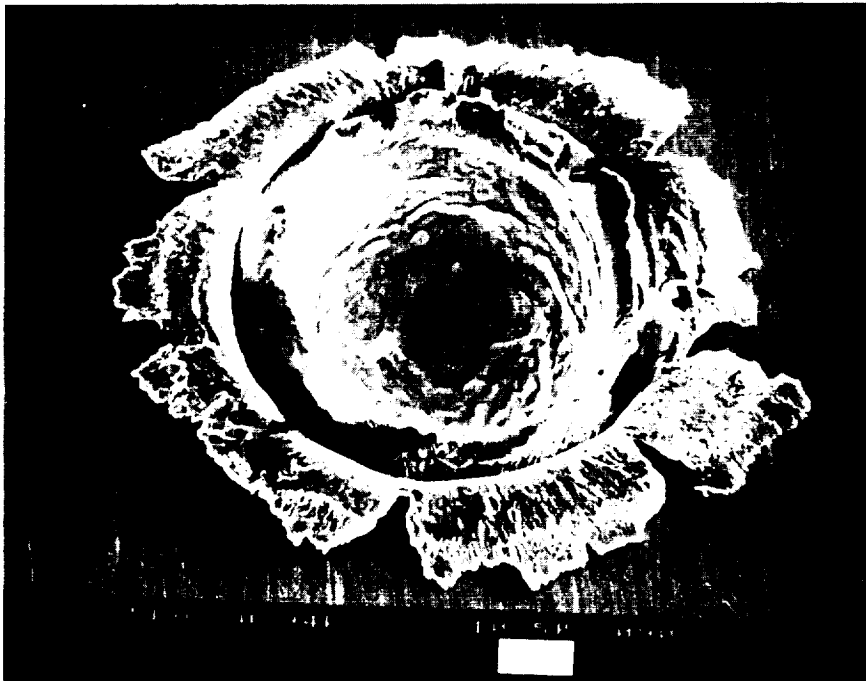
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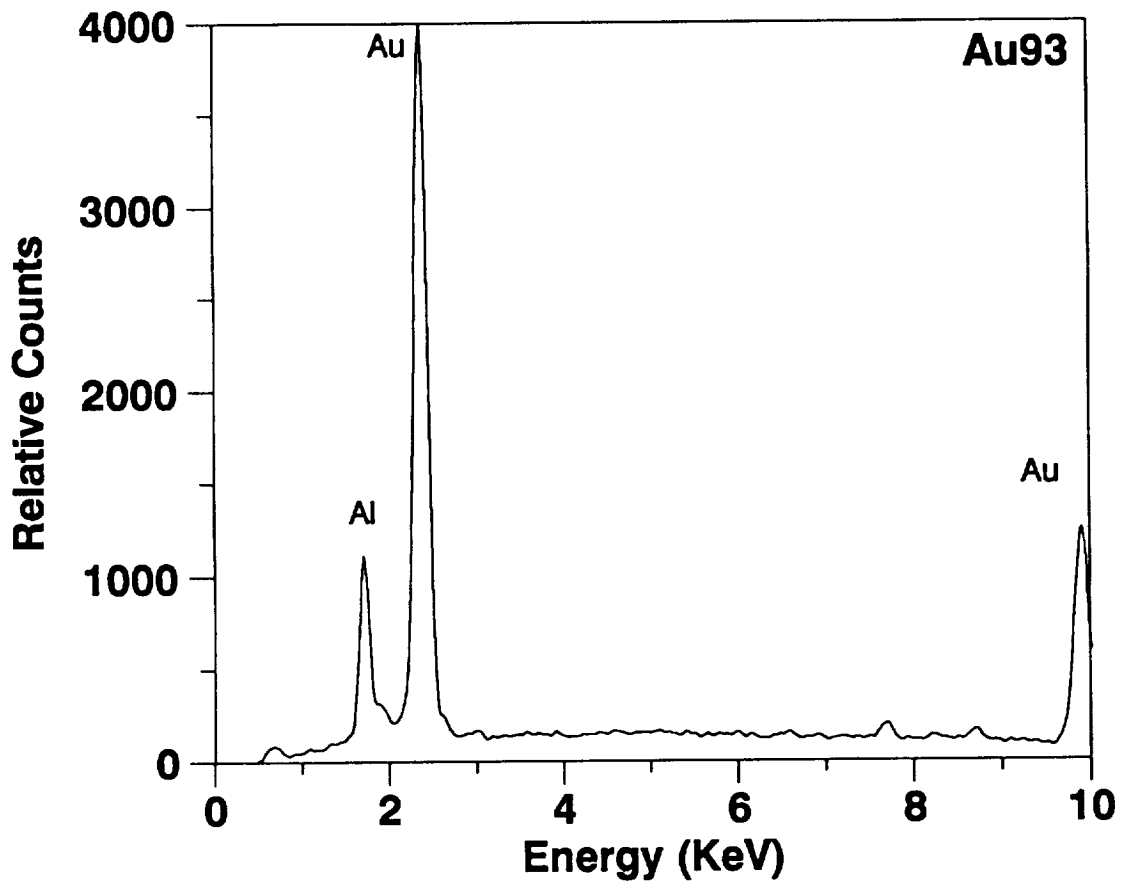


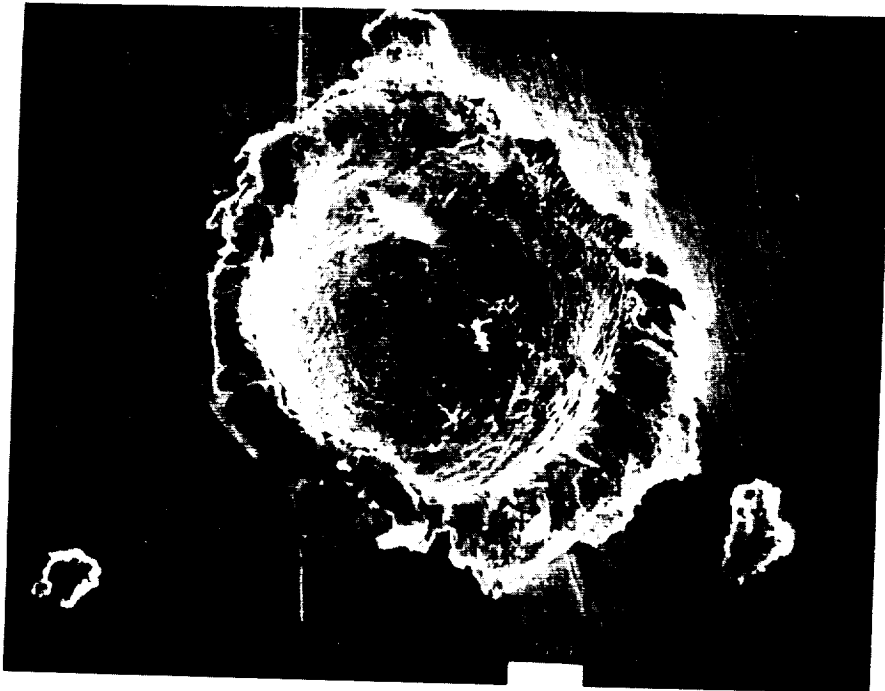
COMPONENT: EOOE
FEATURE: 92
CORE: LD-37
DIAMETER: 30 μm
ORIGIN: Unknown



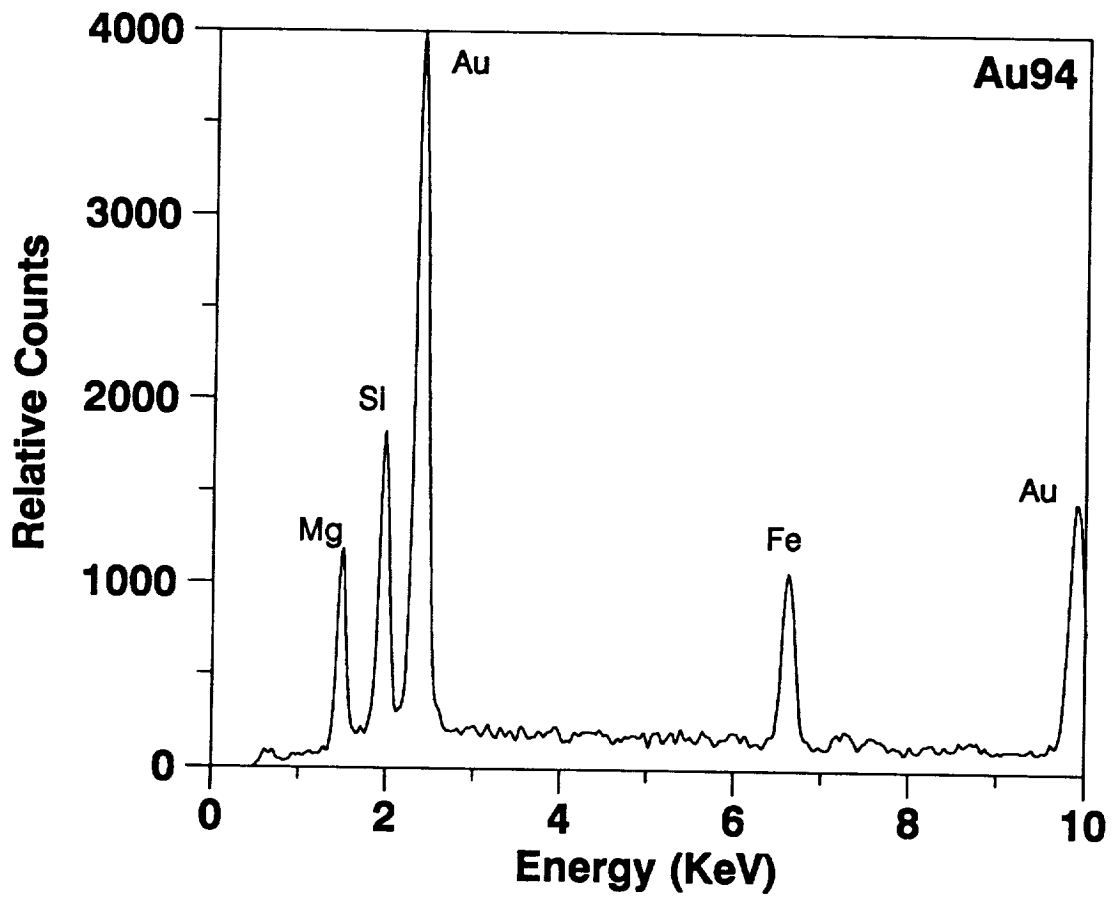


COMPONENT: EOOE
FEATURE: 93
CORE: LD-19
DIAMETER: 60 μm
ORIGIN: Man-made



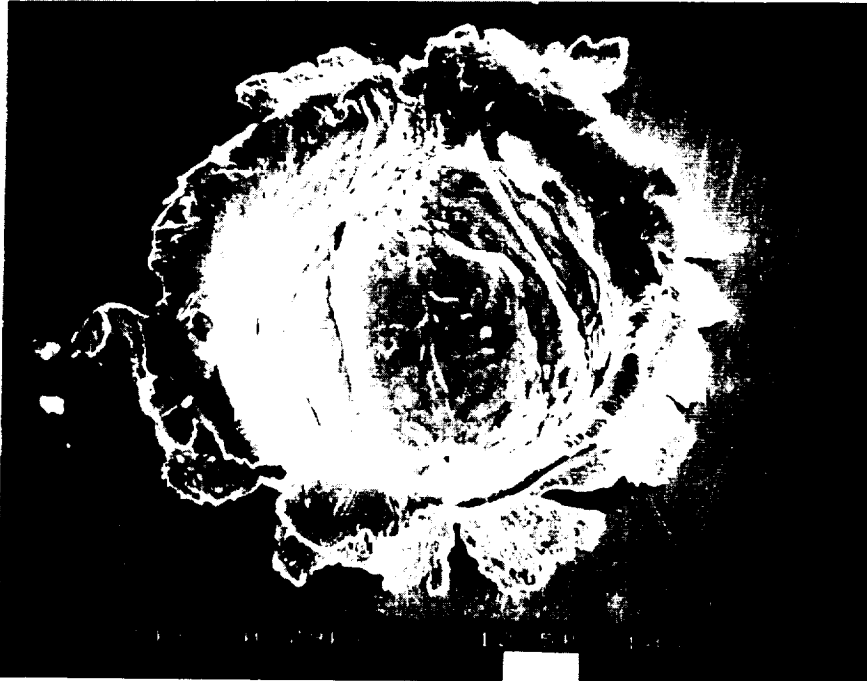


COMPONENT: EOOE
FEATURE: 94
CORE: LD-36
DIAMETER: 35 μm
ORIGIN: Natural



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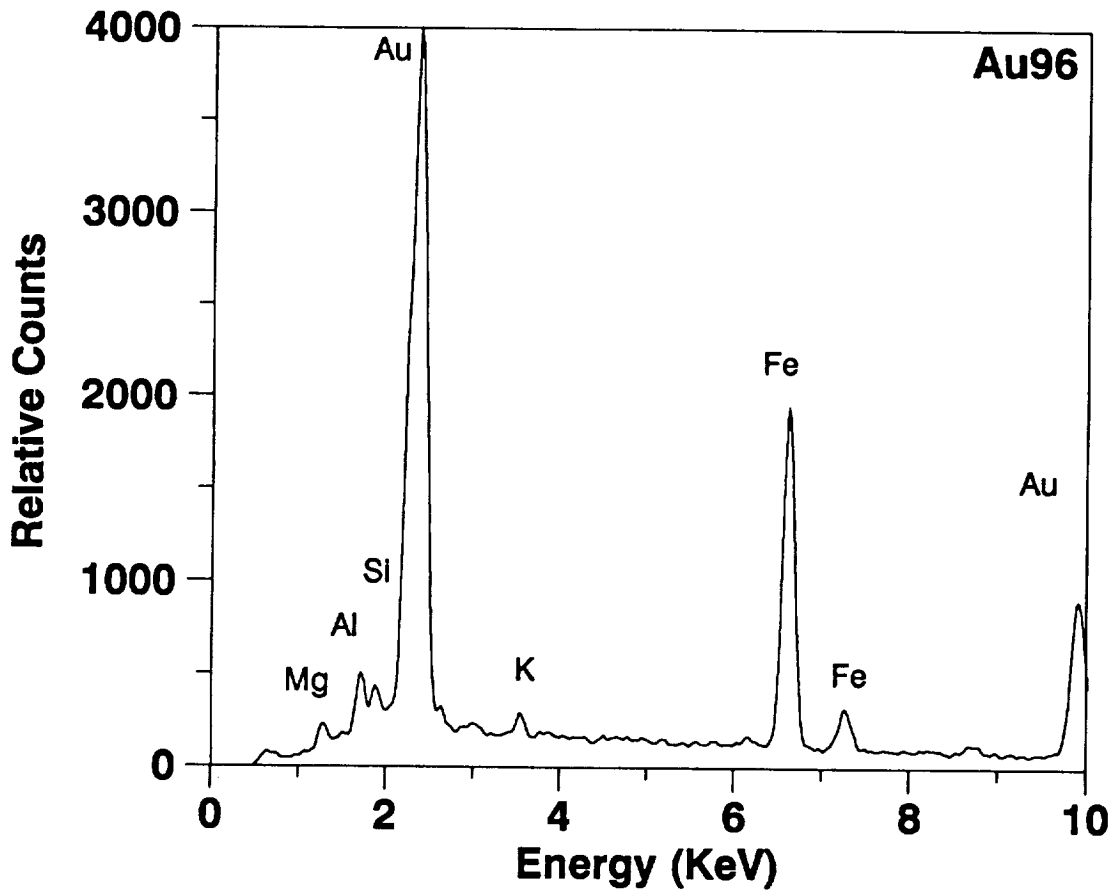
COMPONENT: EOOE

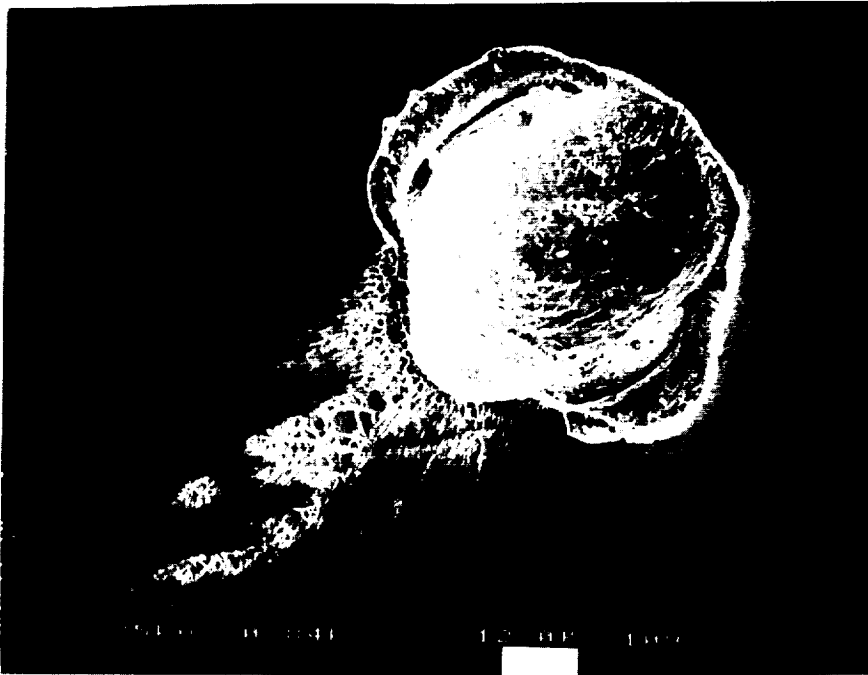
FEATURE: 96

CORE: LD-31

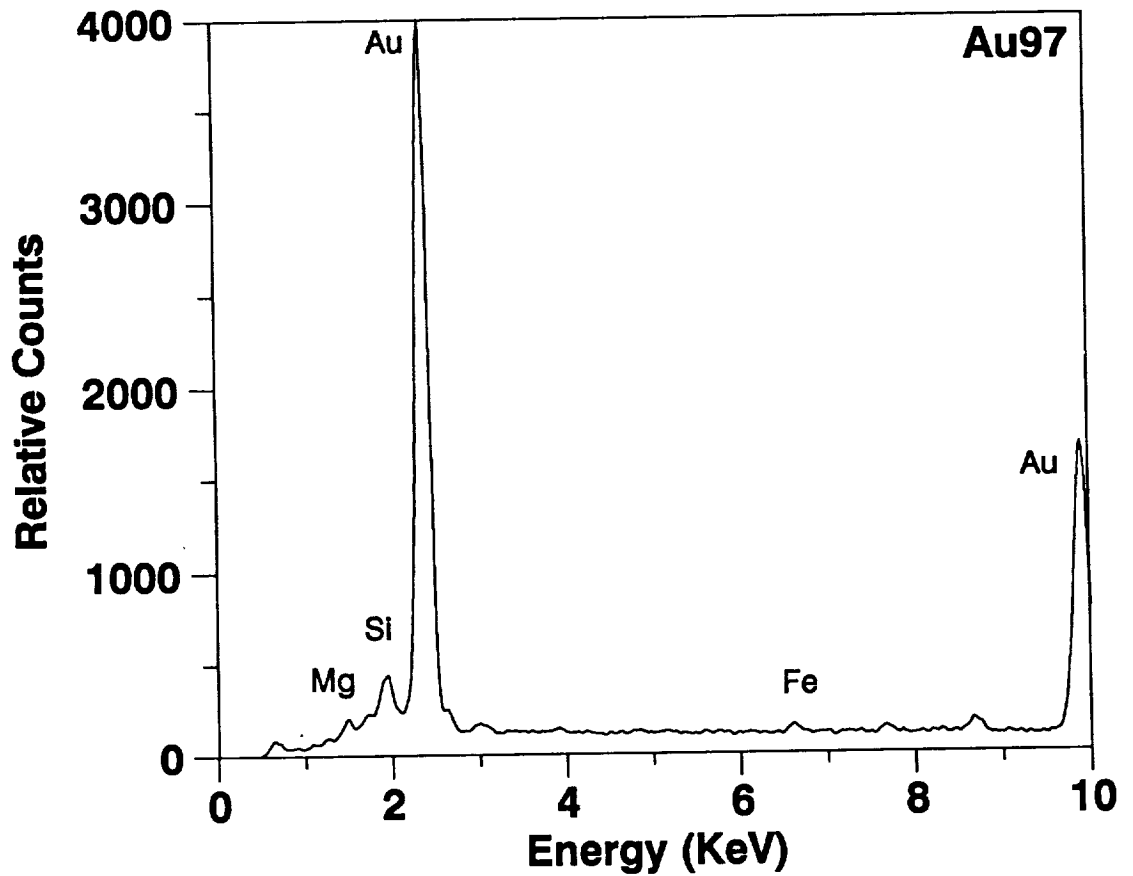
DIAMETER: 70 μm

ORIGIN: Natural



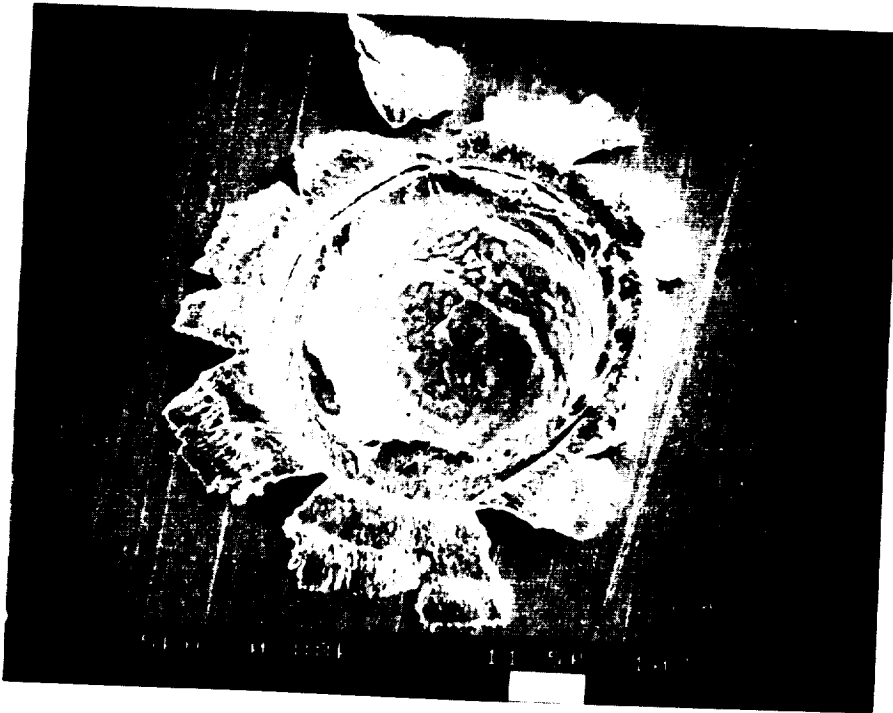


COMPONENT: EOOE
FEATURE: 97
CORE: LD-32
DIAMETER: 50 μm
ORIGIN: Natural

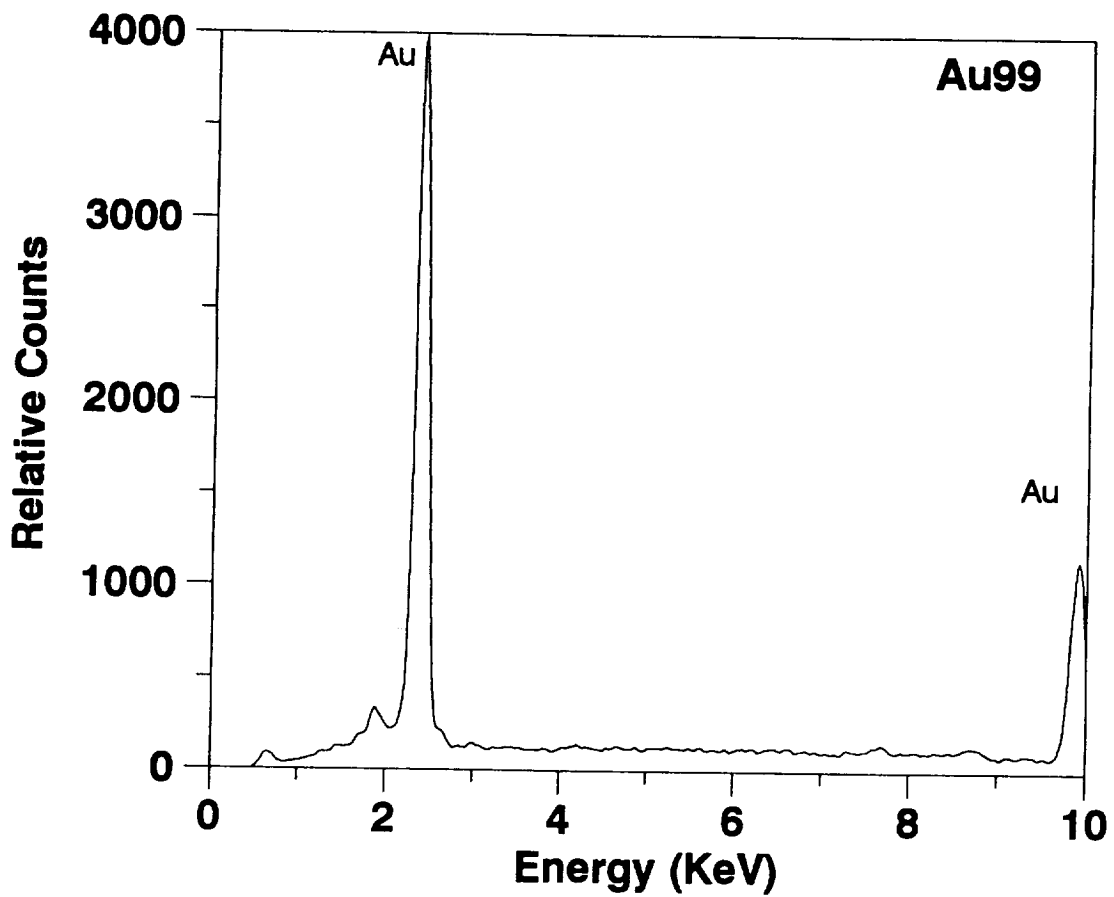


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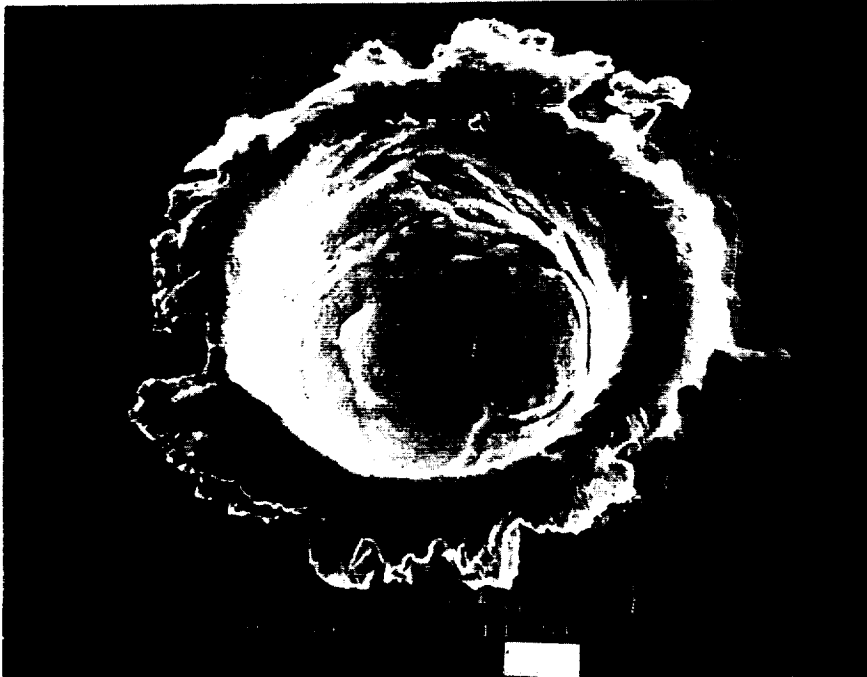


COMPONENT: EOOE
FEATURE: 99
CORE: LD-26
DIAMETER: 50 μ m
ORIGIN: Unknown

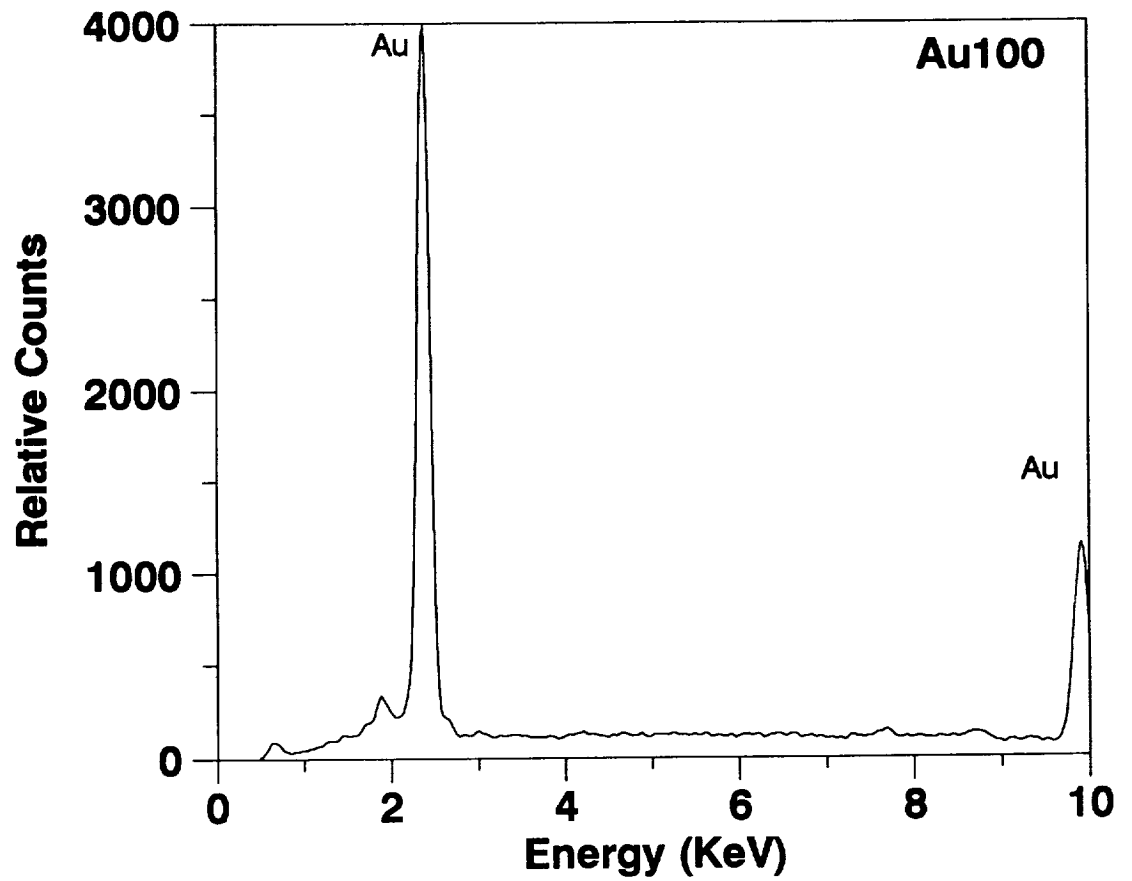


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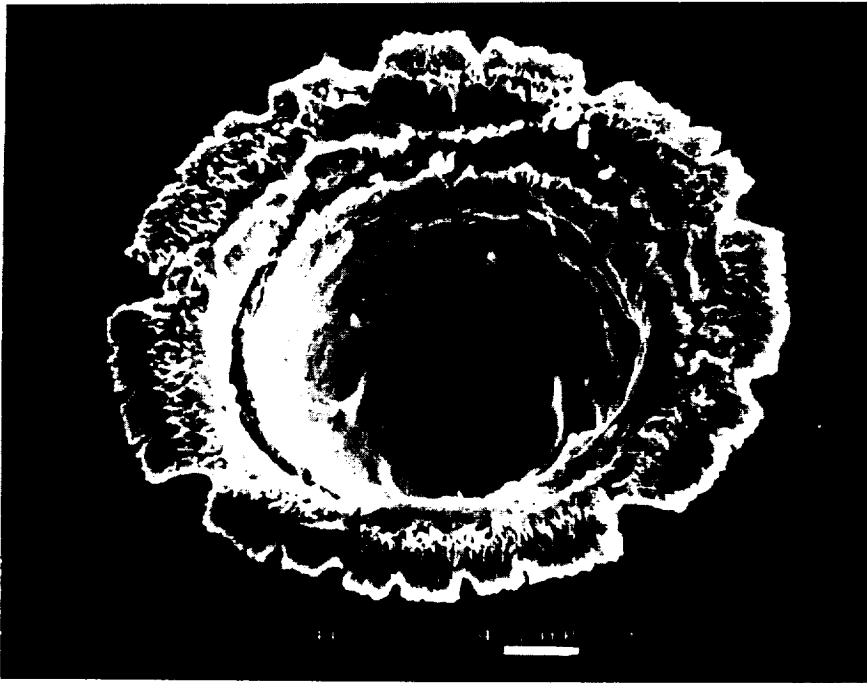


COMPONENT: EOOE
FEATURE: 100
CORE: LD-30
DIAMETER: 50 μ m
ORIGIN: Unknown

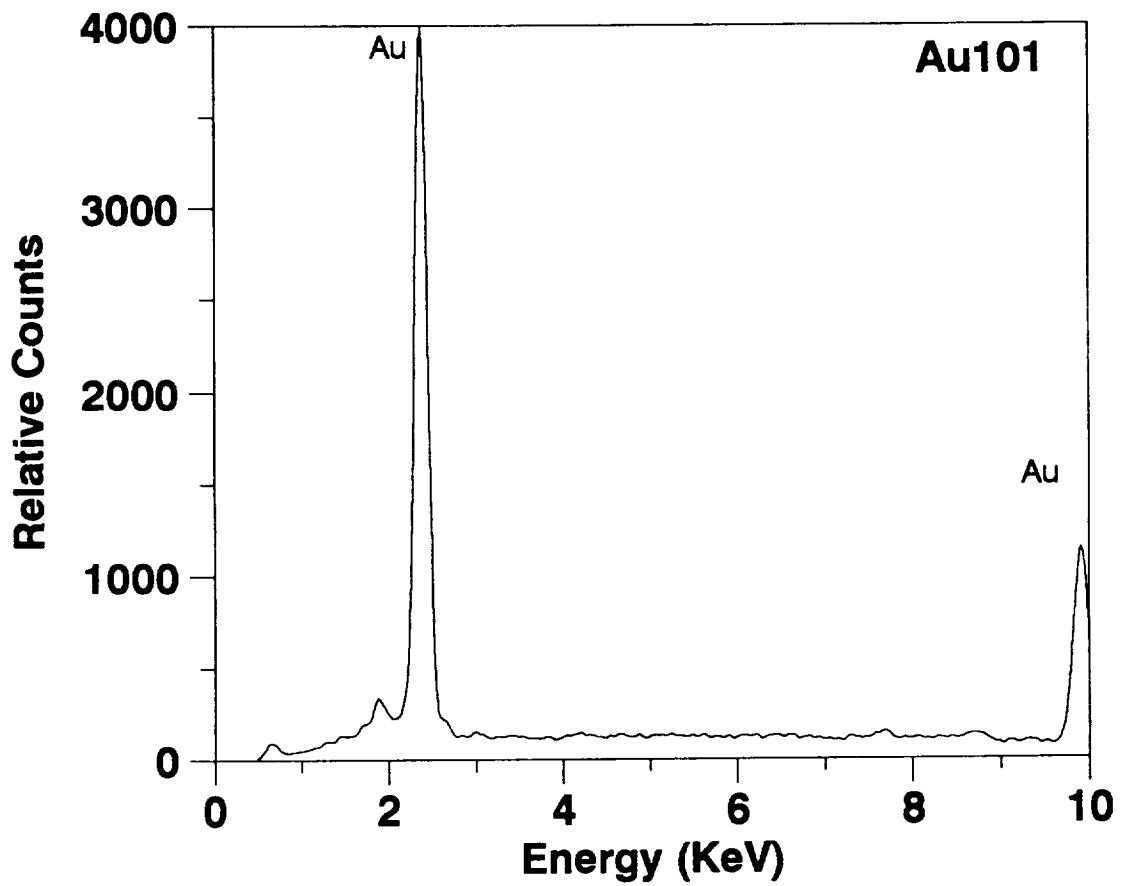


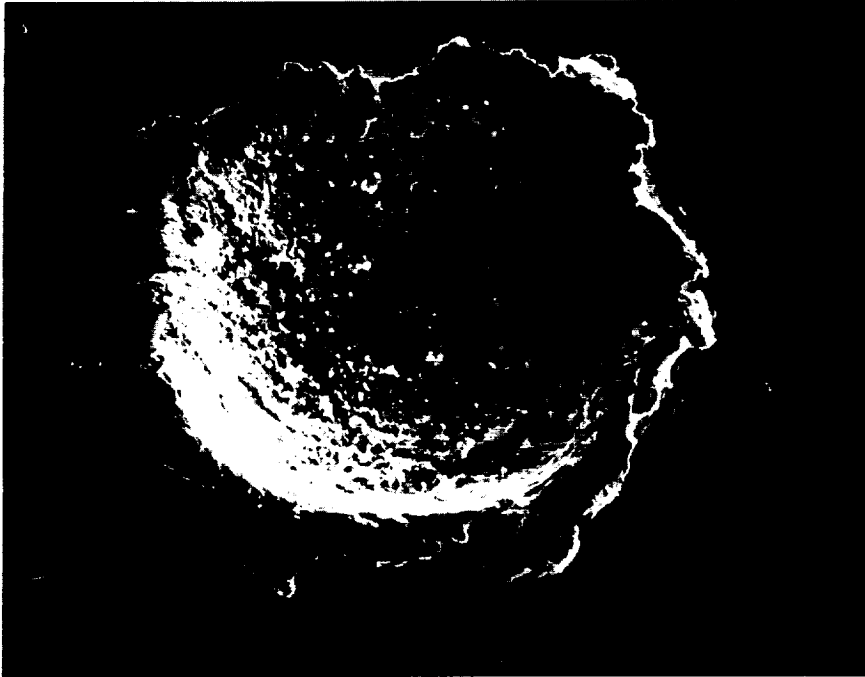
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COMPONENT: EOOE
FEATURE: 101
CORE: LD-33
DIAMETER: 20 μm
ORIGIN: Unknown





COMPONENT: EOOE

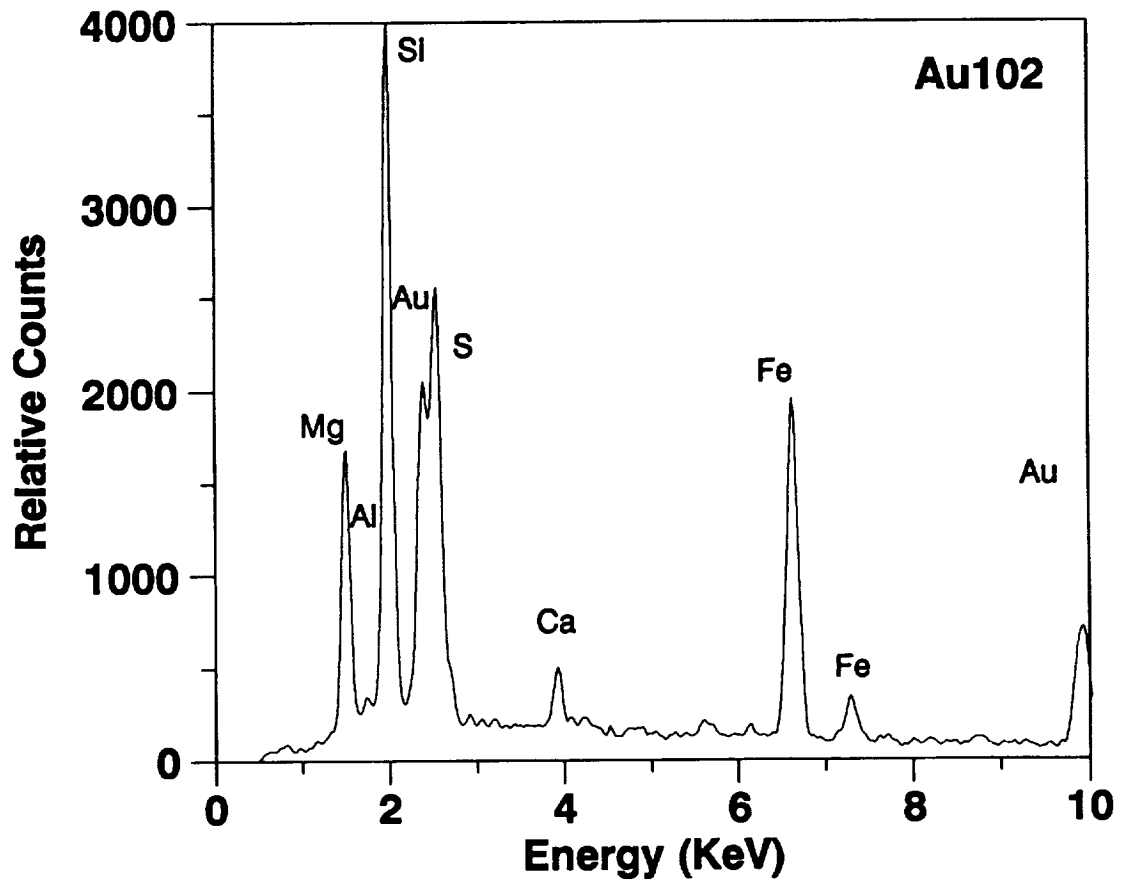
FEATURE: 102

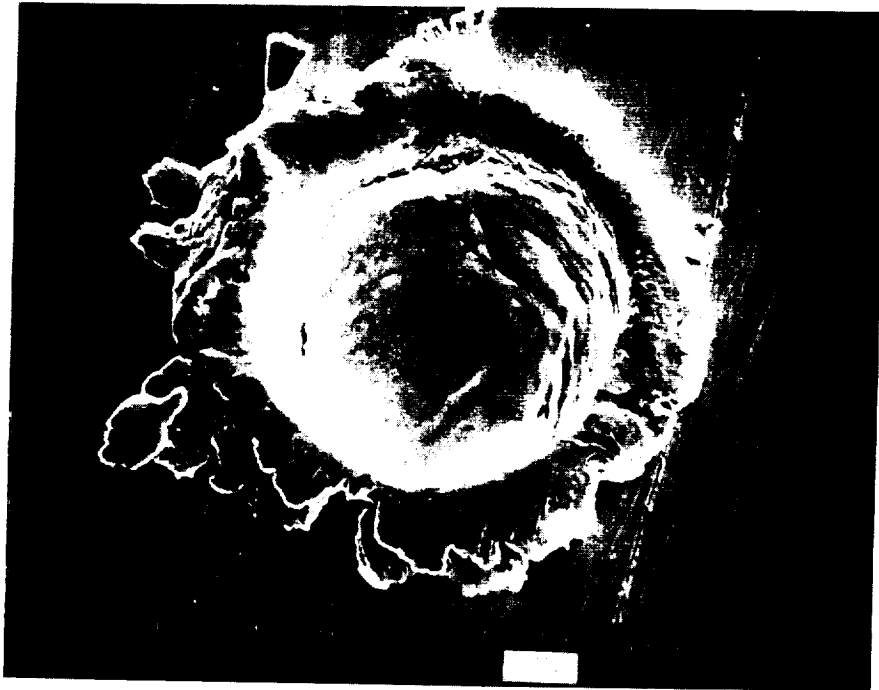
CORE: LD-22

DIAMETER: 240 μm

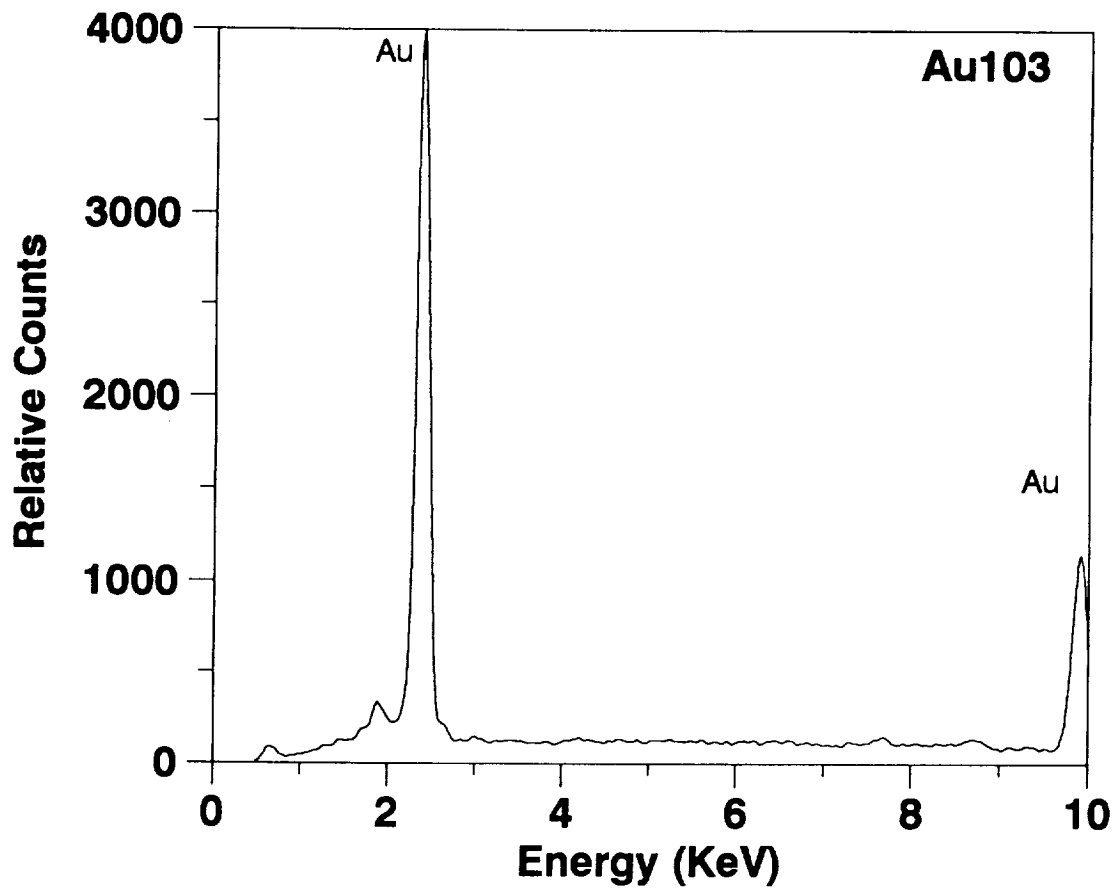
ORIGIN: Natural

CLASS: Chondritic



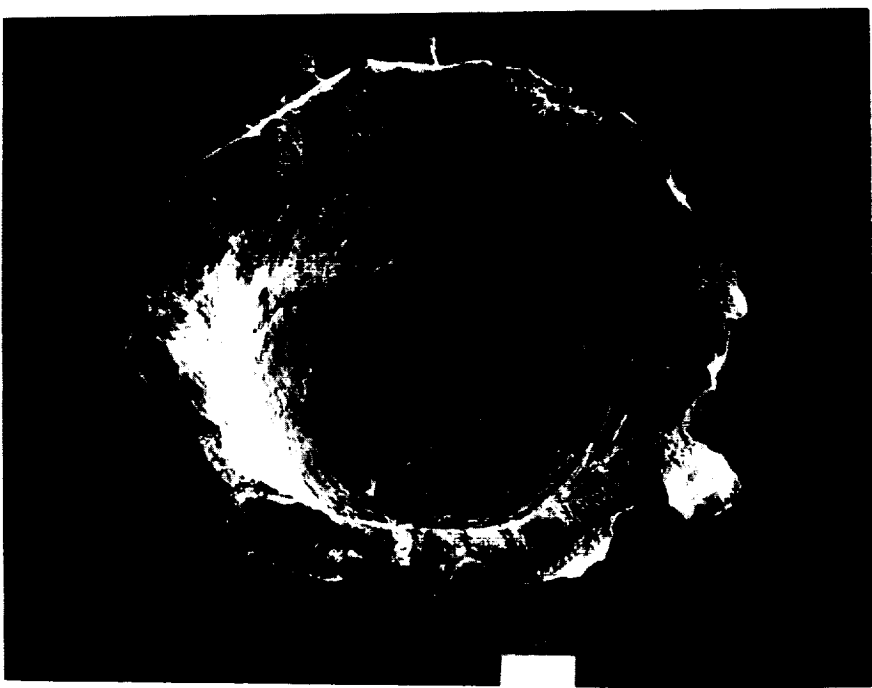


COMPONENT: EOOE
FEATURE: 103
CORE: LD-27
DIAMETER: 70 μm
ORIGIN: Unknown

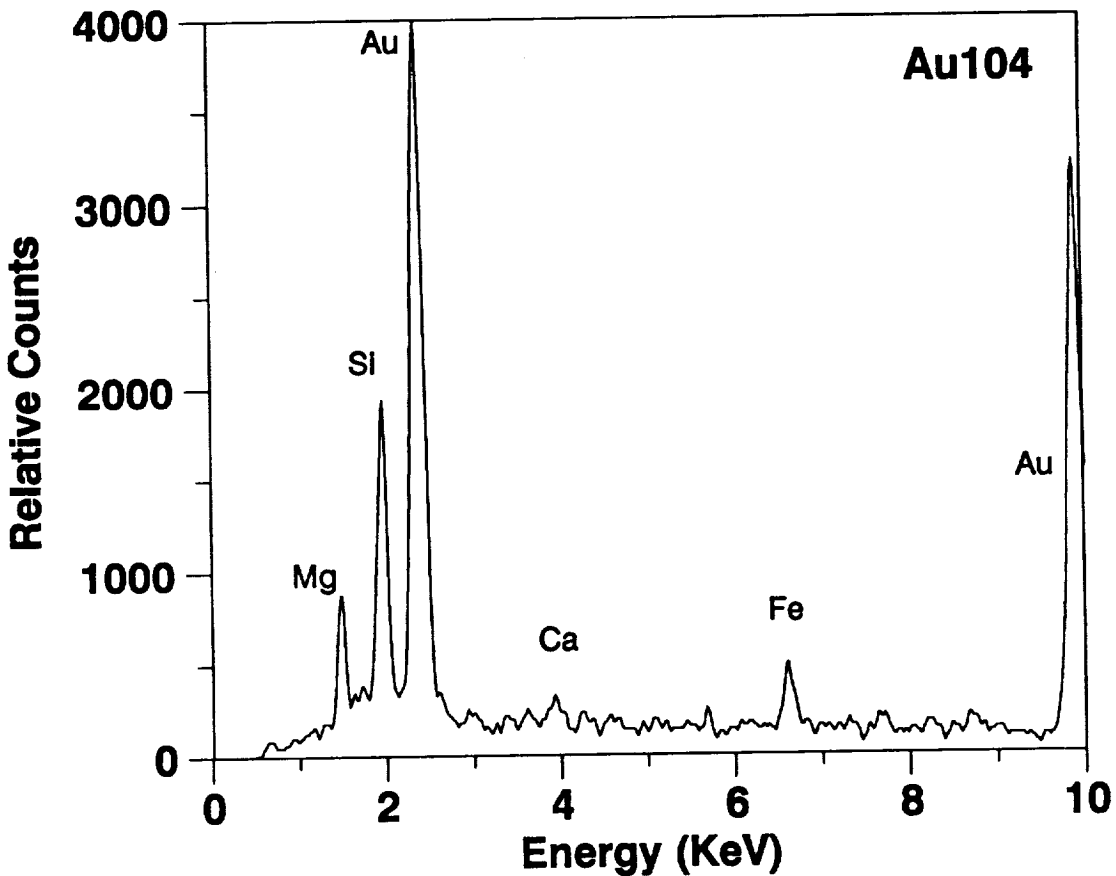


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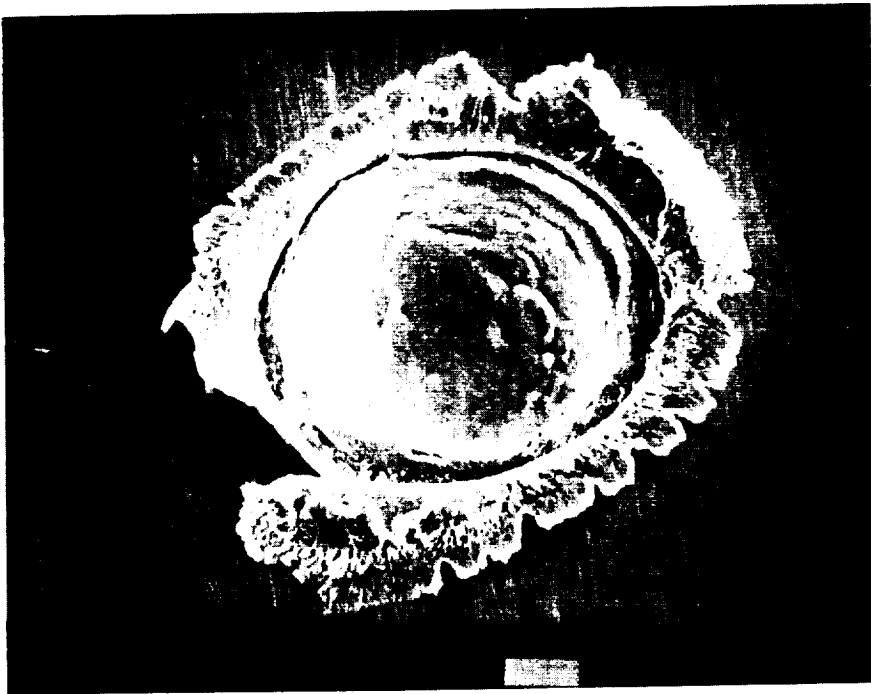


COMPONENT: EOOE
FEATURE: 104
CORE: LD-15
DIAMETER: 440 μ m
ORIGIN: Natural



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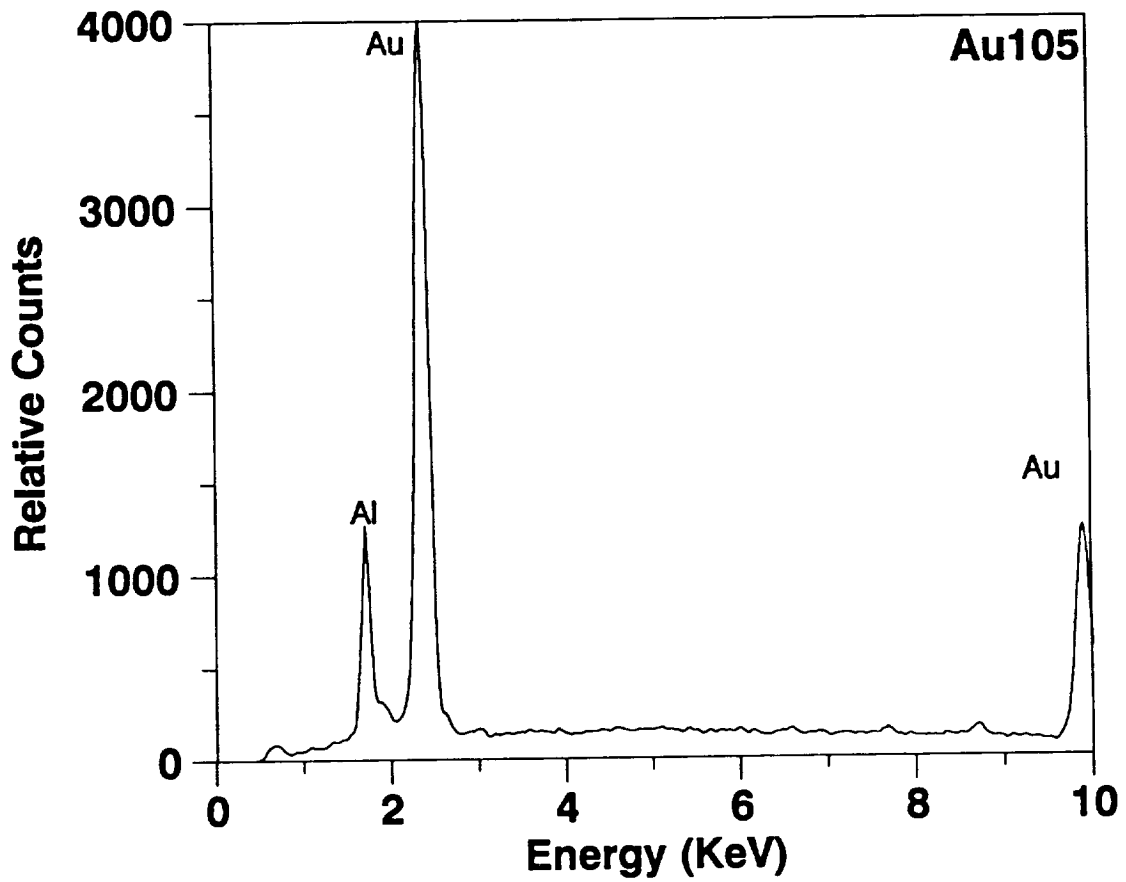
COMPONENT: EOOE

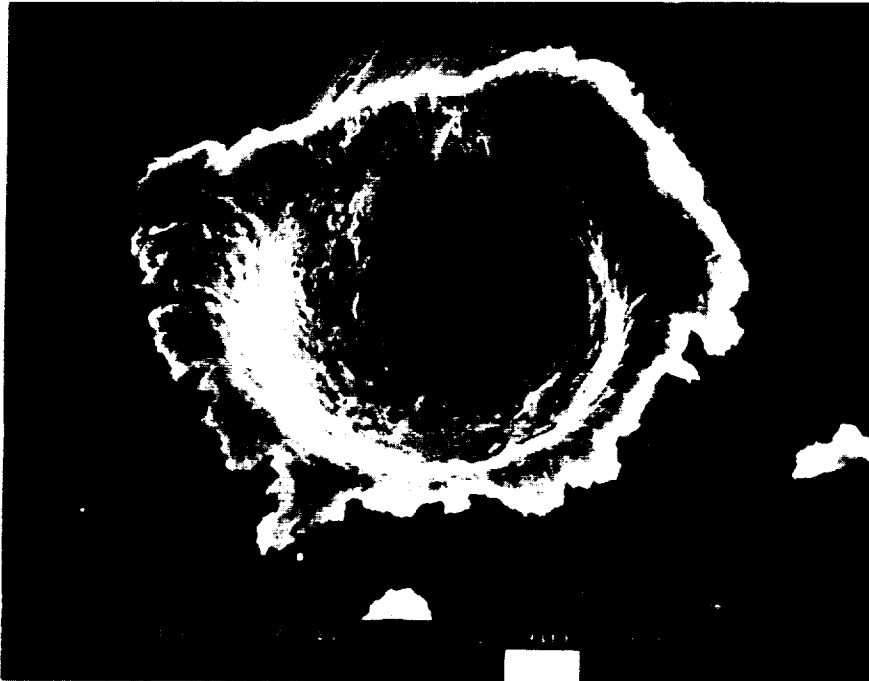
FEATURE: 105

CORE: LD-18

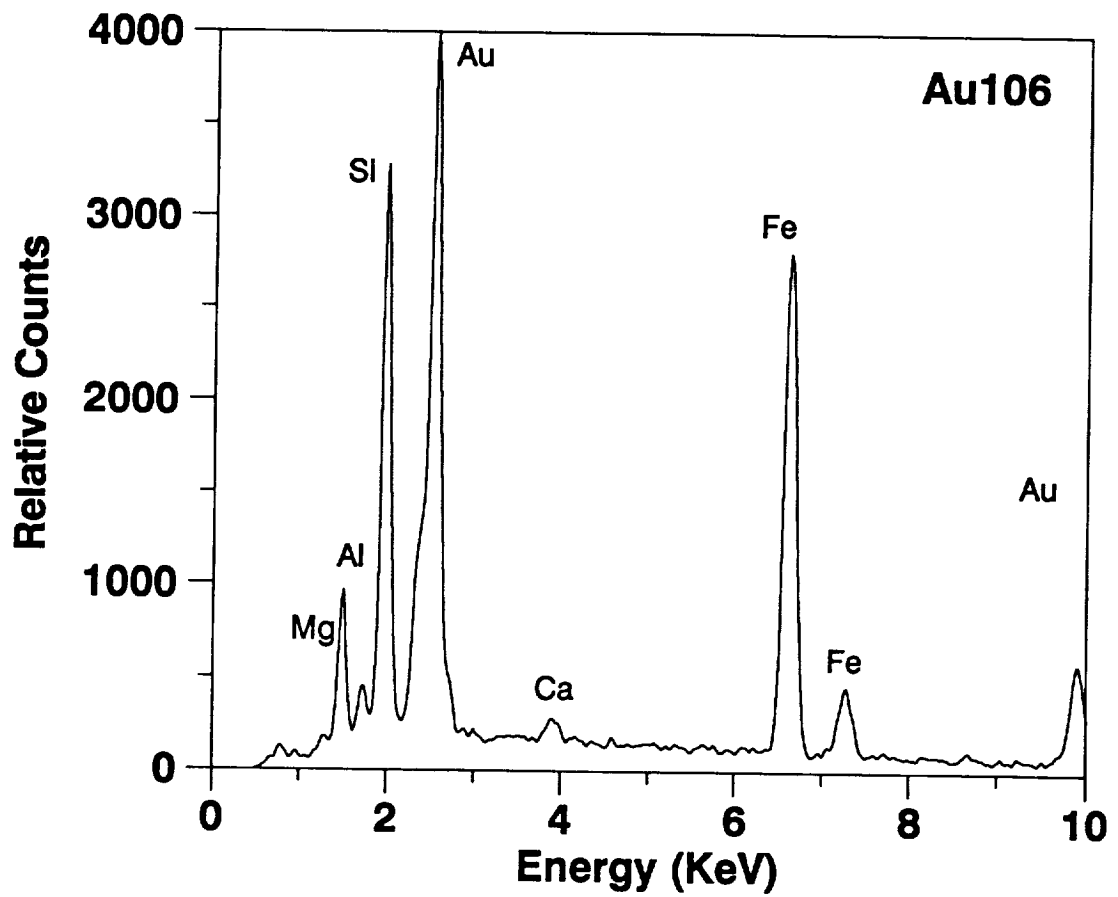
DIAMETER: 30 μ m

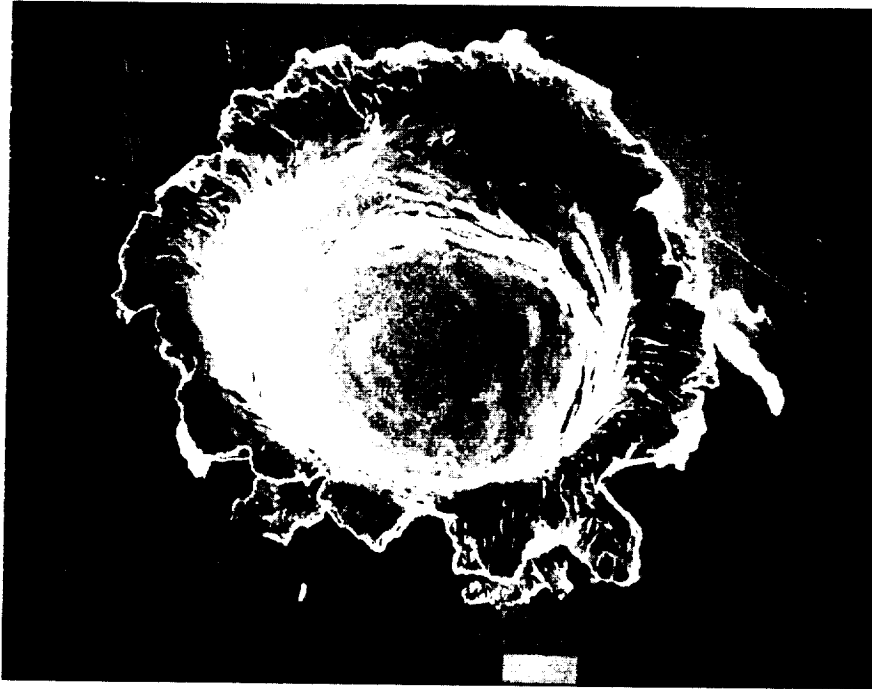
ORIGIN: Man-made





COMPONENT: EOOE
FEATURE: 106
CORE: LD-28
DIAMETER: 10 μm
ORIGIN: Natural
CLASS: Chondritic





COMPONENT: EOOE

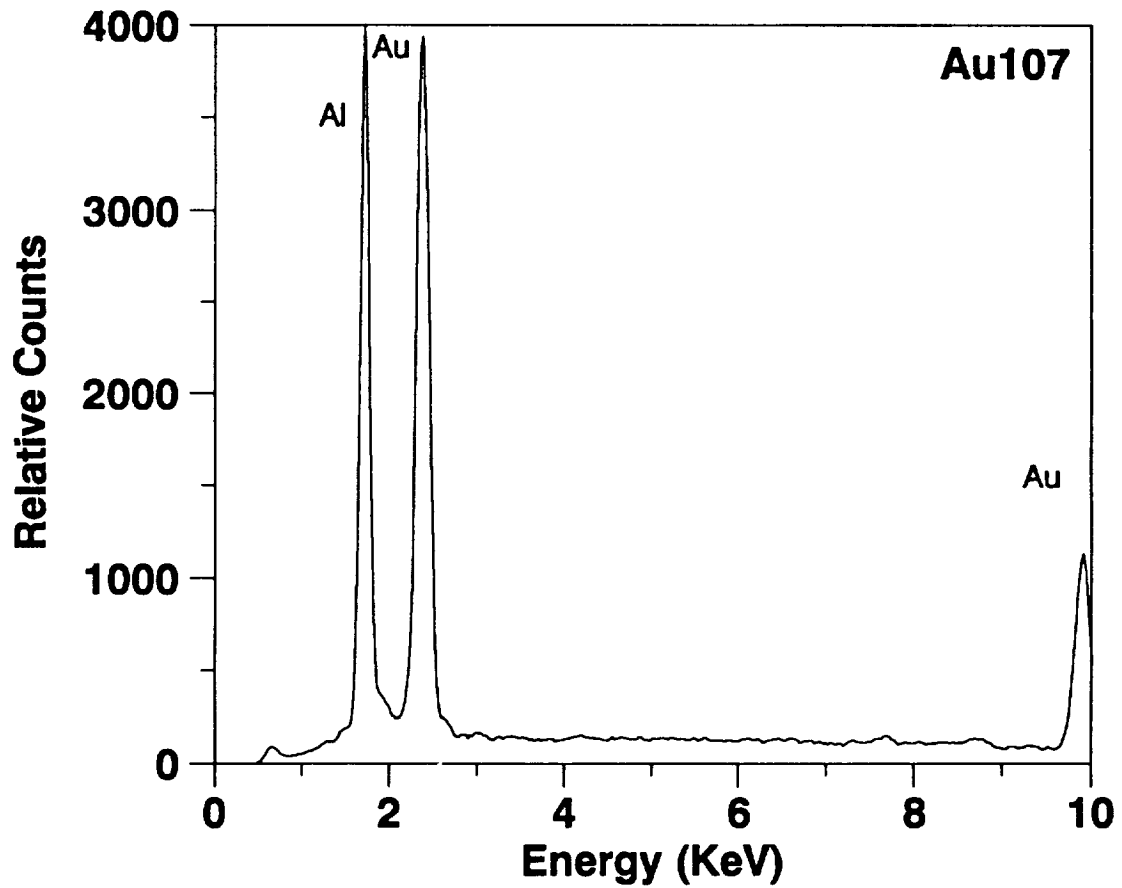
FEATURE: 107

CORE: LD-14

DIAMETER: 105 μ m

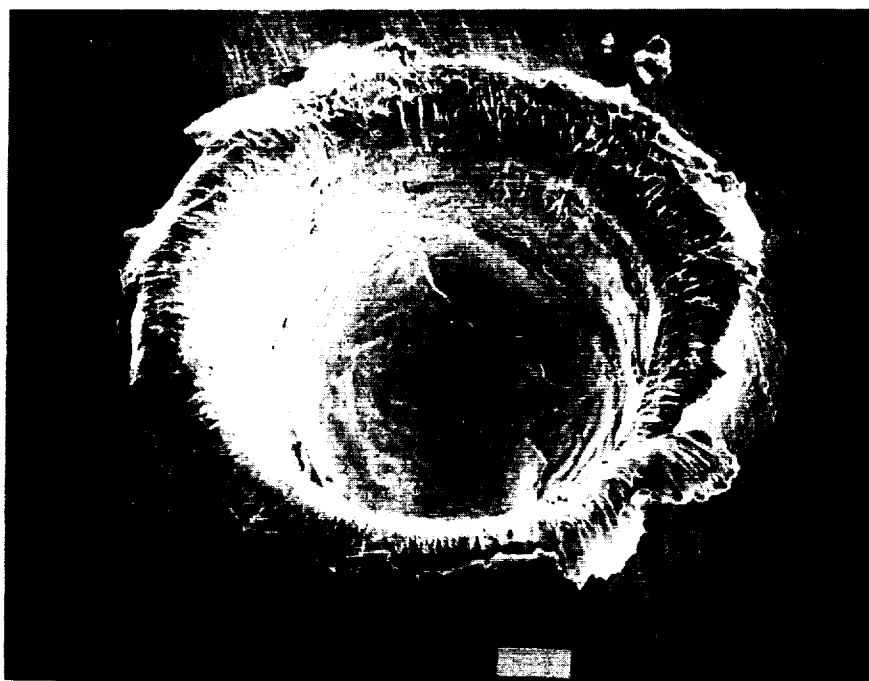
ORIGIN: Man-made

CLASS: Debris



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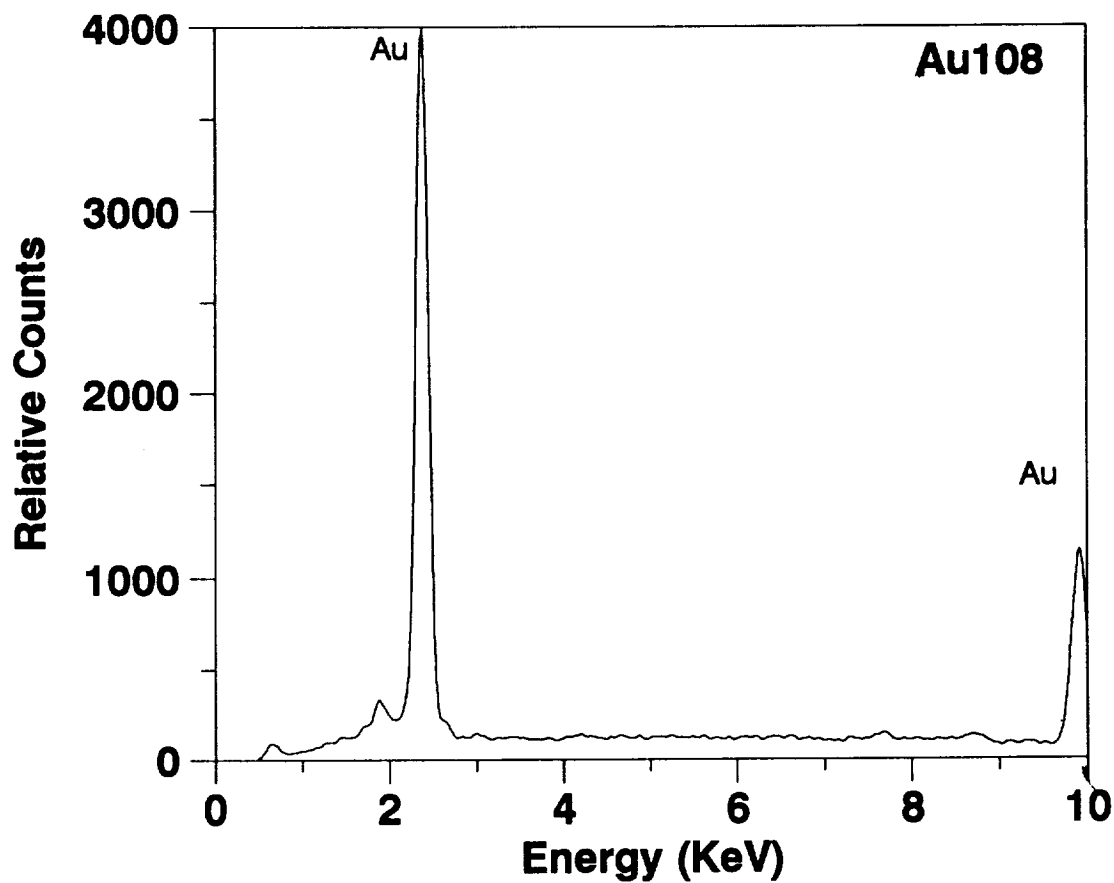
COMPONENT: EOOE

FEATURE: 108

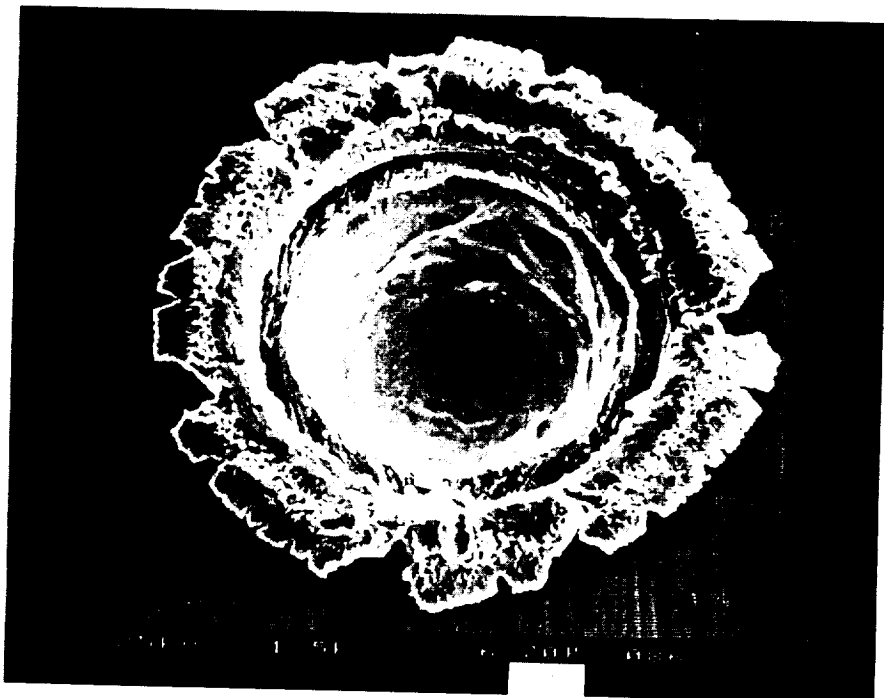
CORE: LD-16

DIAMETER: 210 μ m

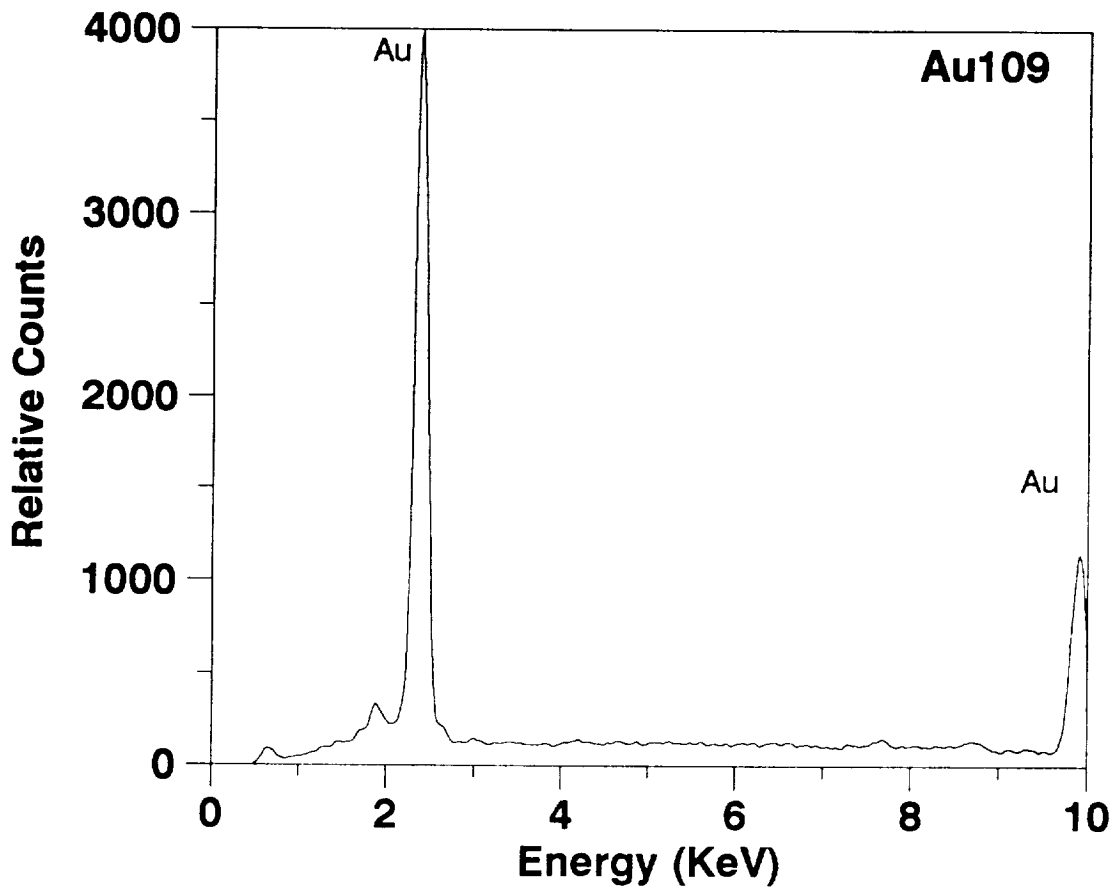
ORIGIN: Unknown



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COMPONENT: EOOE
FEATURE: 109
CORE: LD-17
DIAMETER: 30 μ m
ORIGIN: Unknown





COMPONENT: EOOE

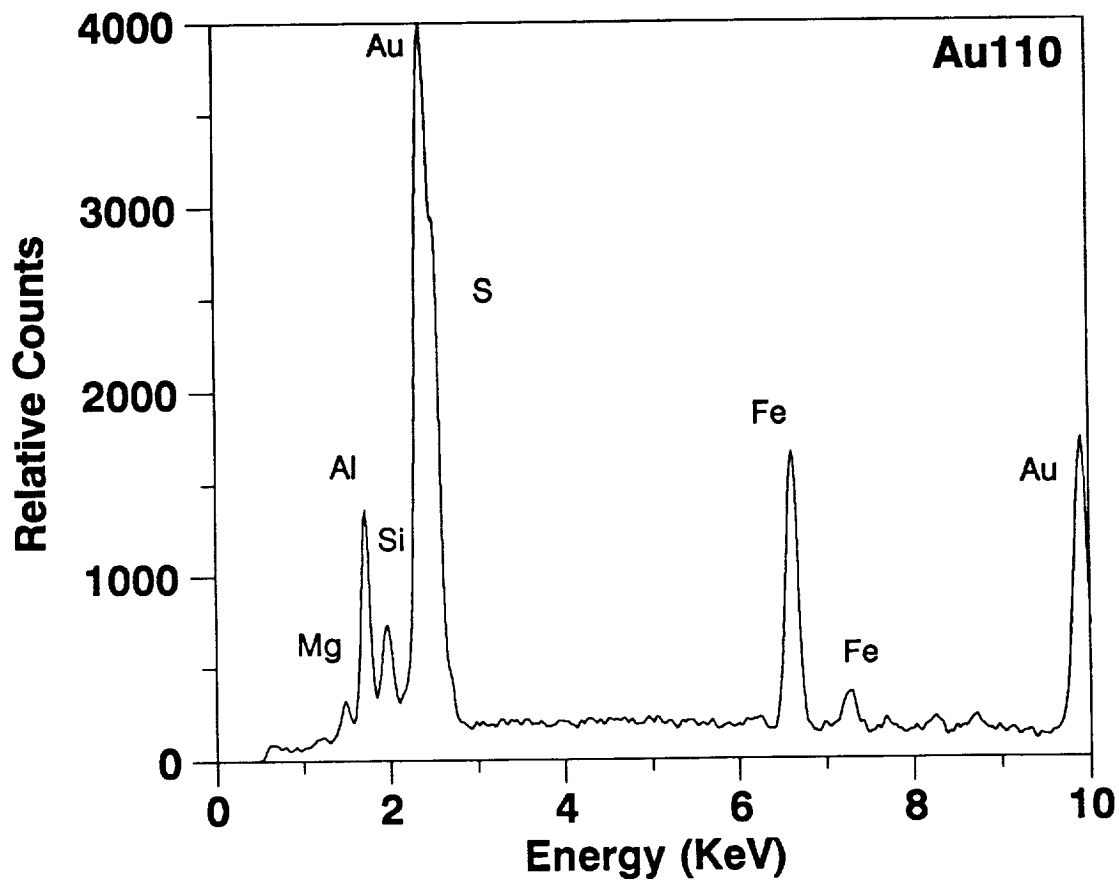
FEATURE: 110

CORE: LD-29

DIAMETER: 170 μm

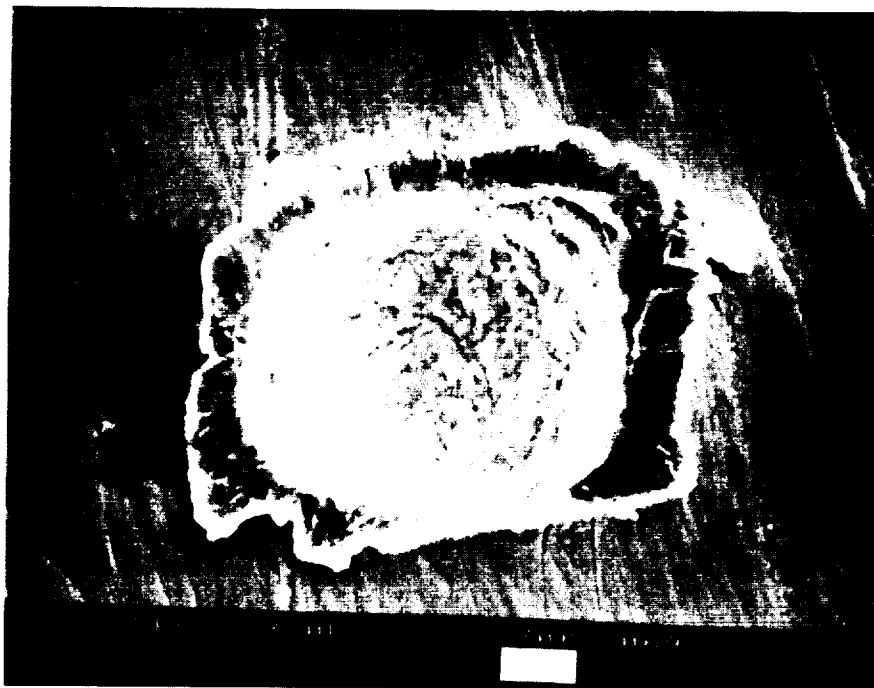
ORIGIN: Natural

CLASS: Chondritic



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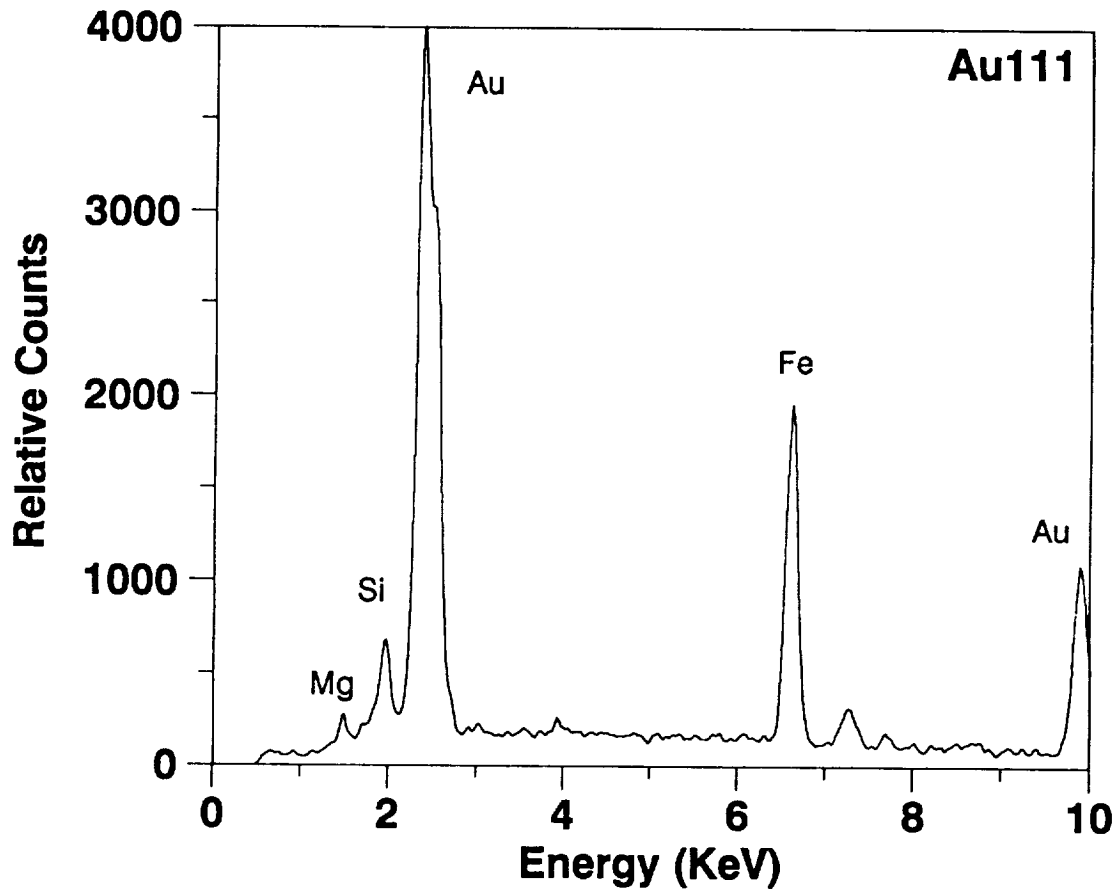
COMPONENT: EOOE

FEATURE: 111

CORE: LD-6

DIAMETER: 15 μ m

ORIGIN: Natural

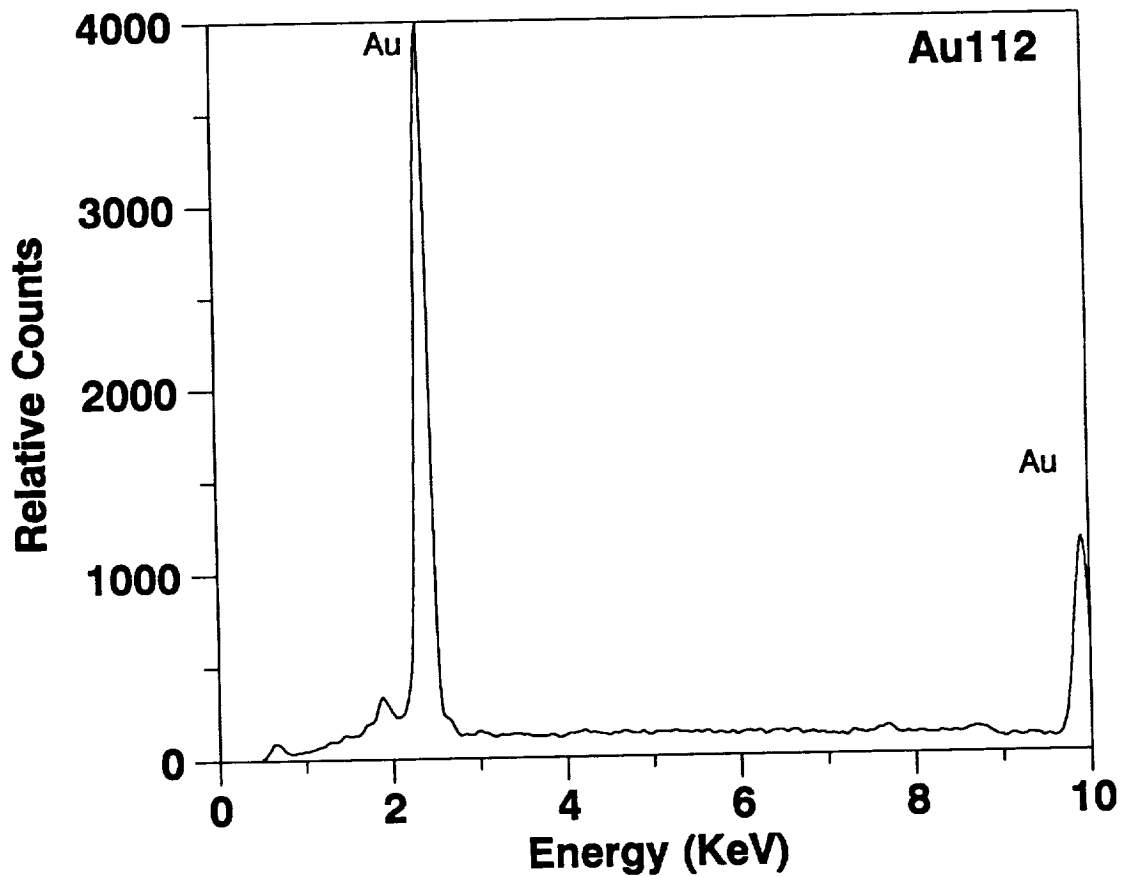


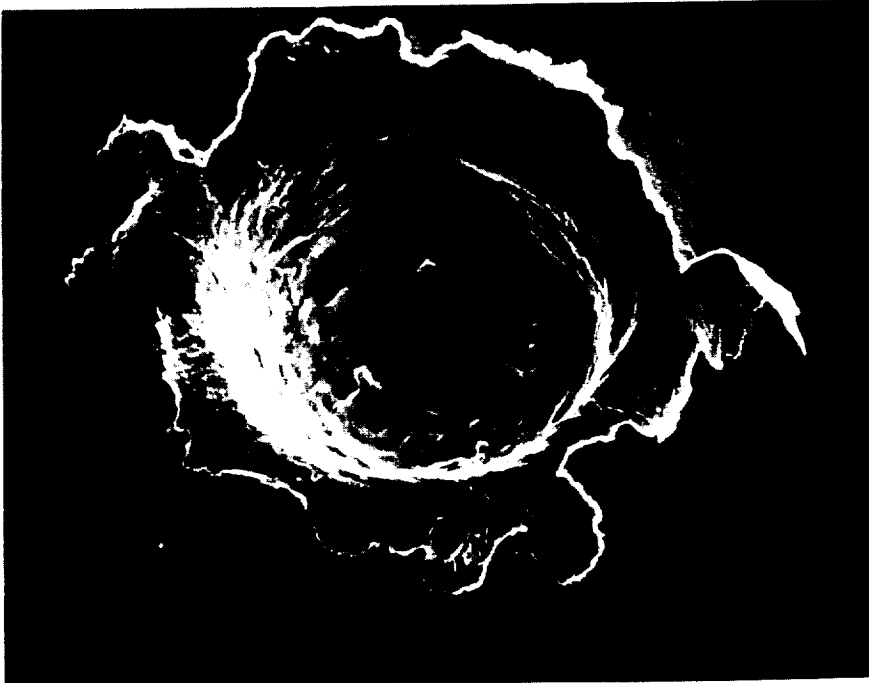
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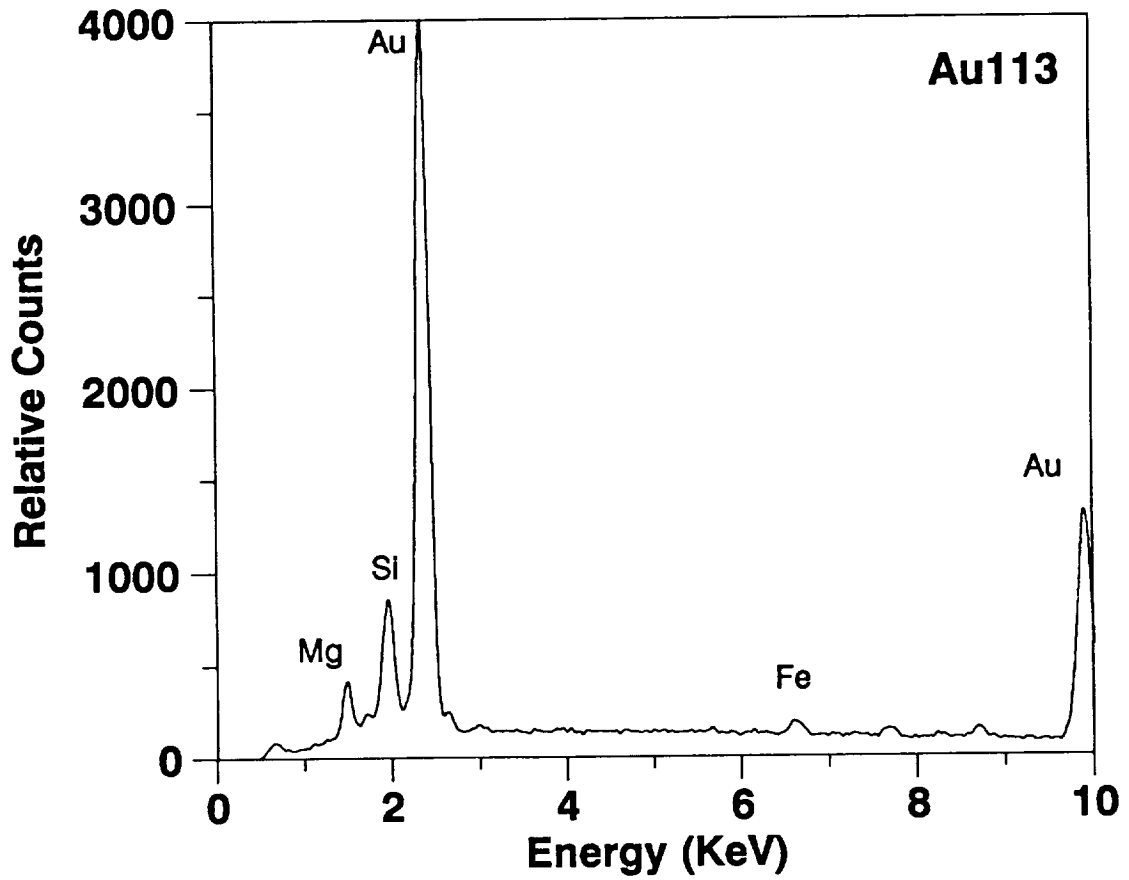


COMPONENT: E00F
FEATURE: 112
CORE: LD-82
DIAMETER: 15 μm
ORIGIN: Unknown



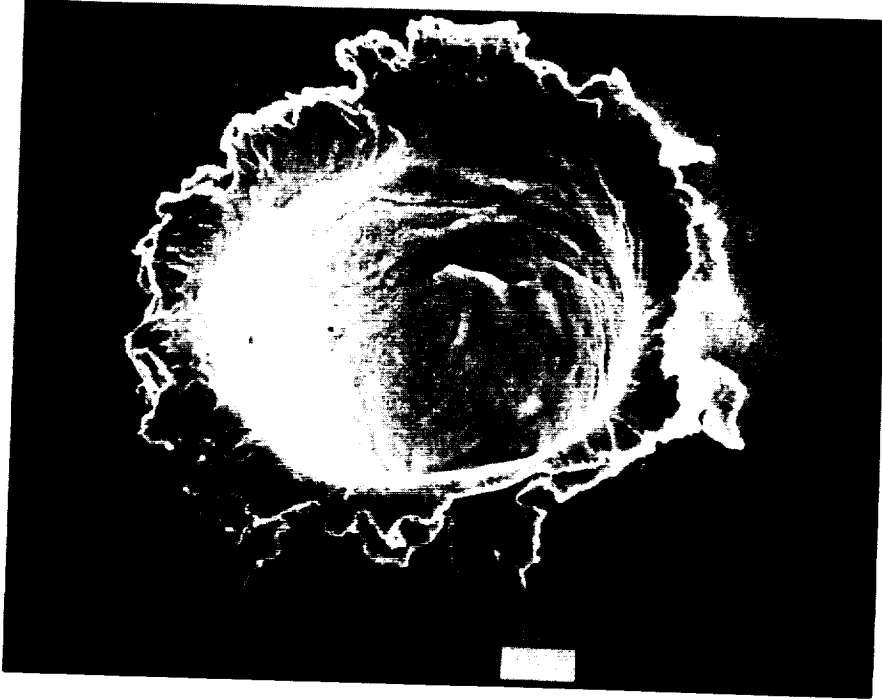


COMPONENT: EEOF
FEATURE: 113
CORE: LD-83
DIAMETER: 55 μm
ORIGIN: Natural
CLASS: Chondritic



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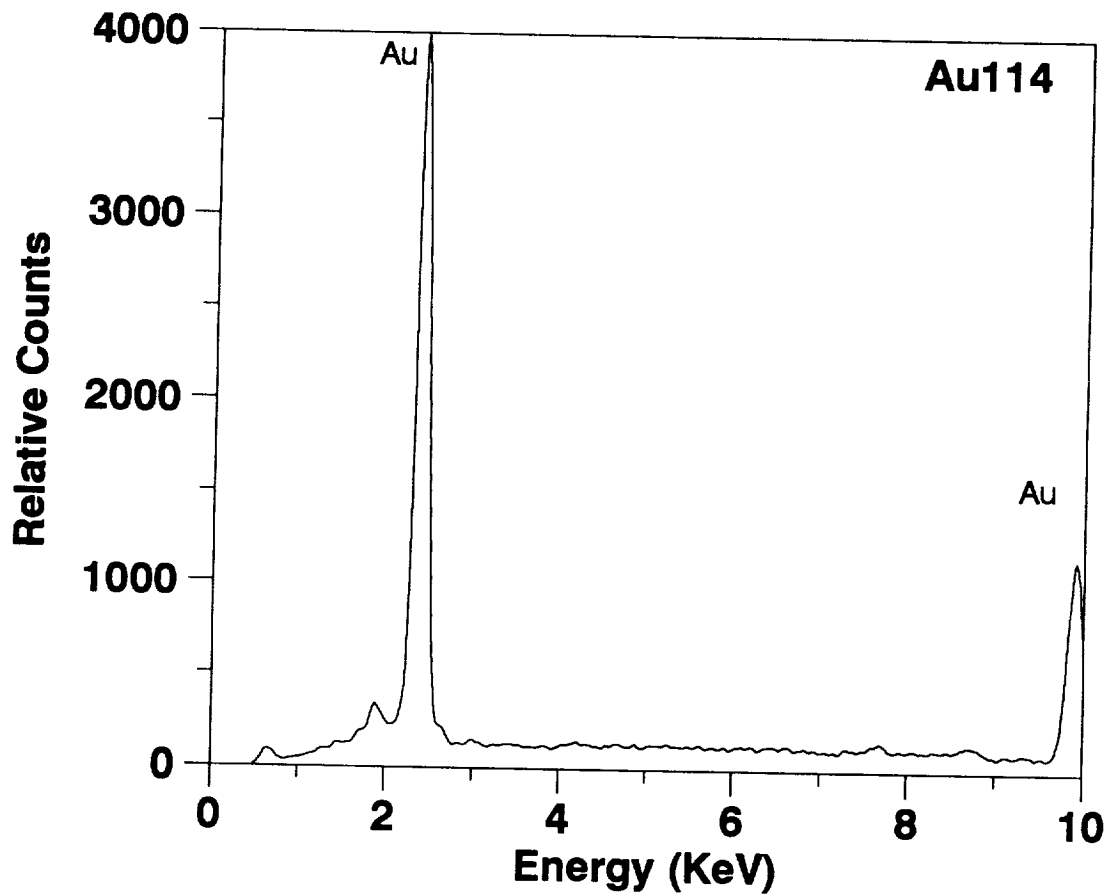
COMPONENT: EOFF

FEATURE: 114

CORE: LD-81

DIAMETER: 40 μm

ORIGIN: Unknown



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COMPONENT: E00F

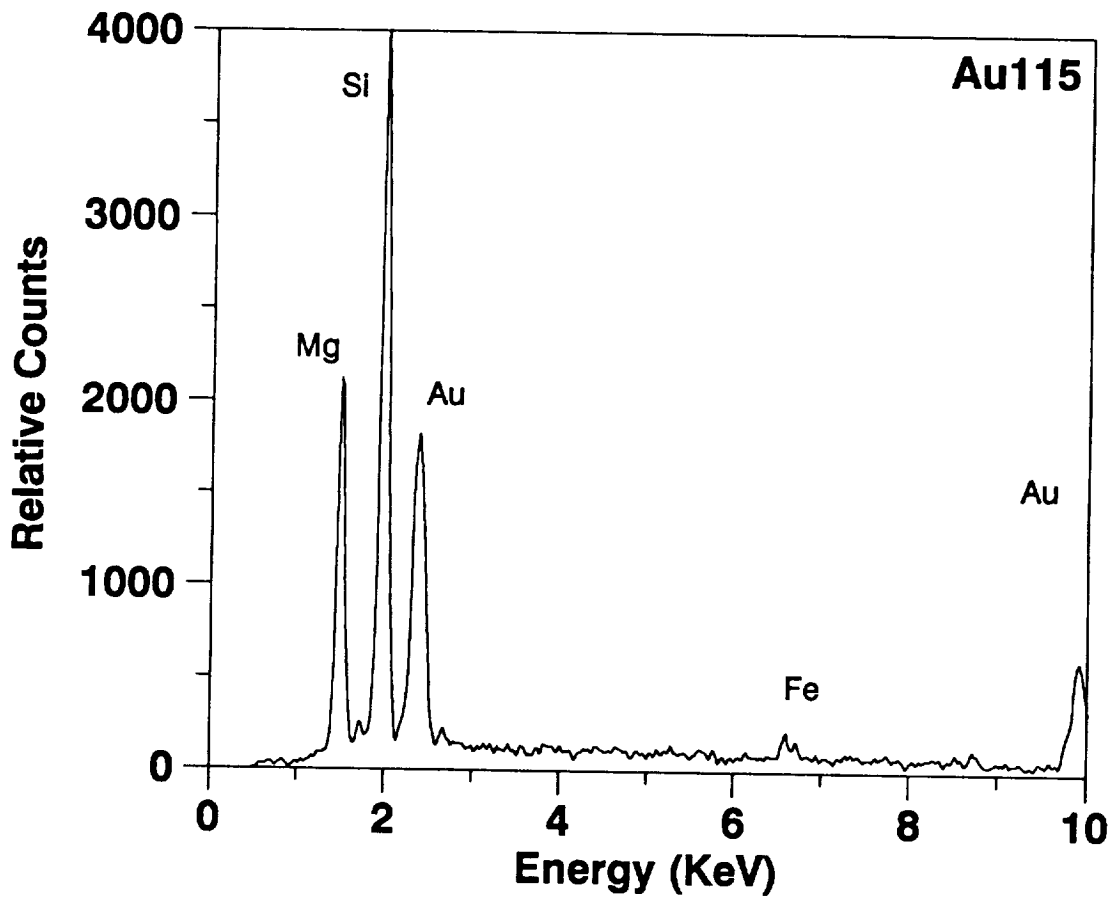
FEATURE: 115

CORE: LD-51

DIAMETER: 55 μm

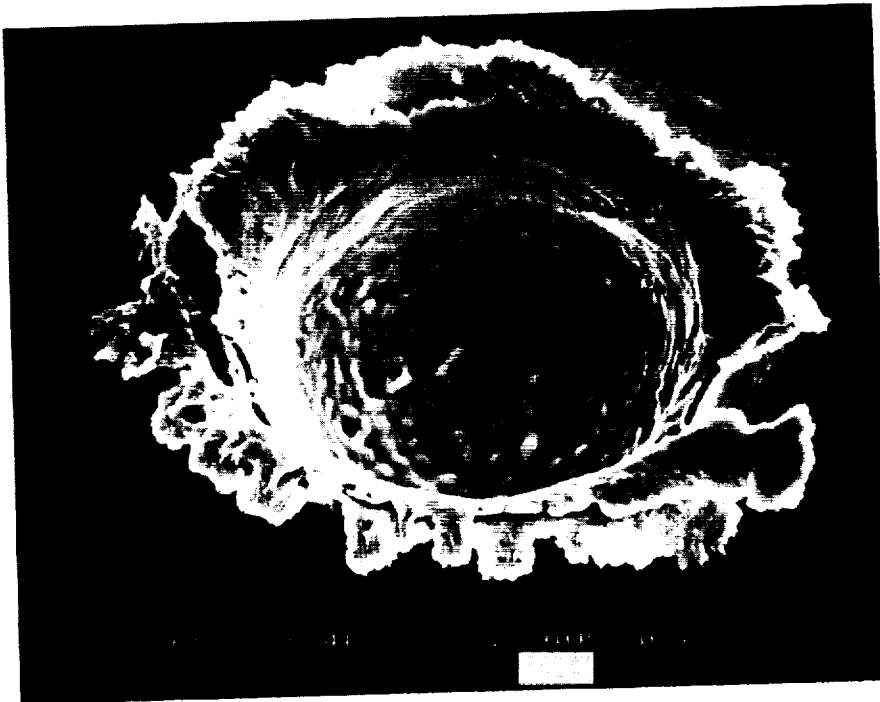
ORIGIN: Natural

CLASS: Chondritic



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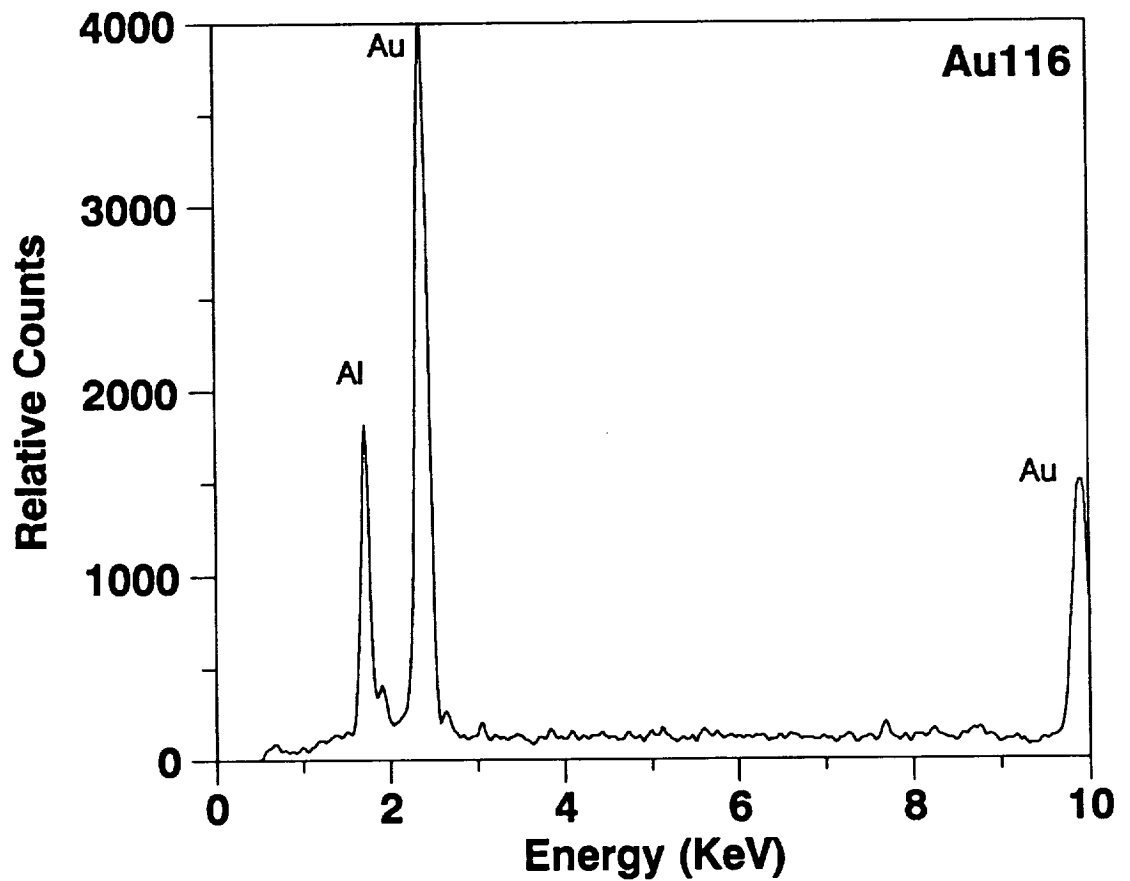
COMPONENT: E00F

FEATURE: 116

CORE: LD-53

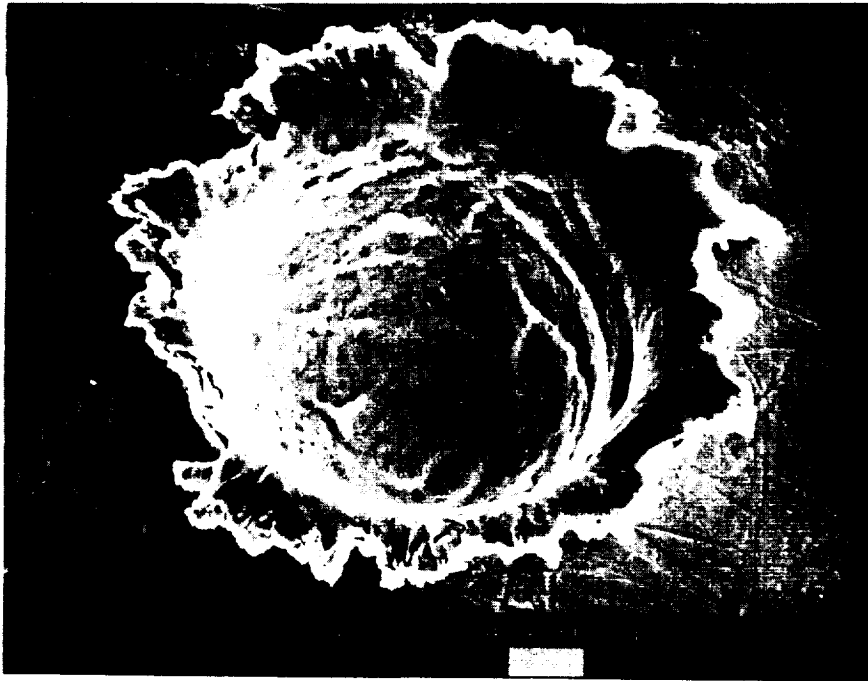
DIAMETER: 10 μm

ORIGIN: Man-made



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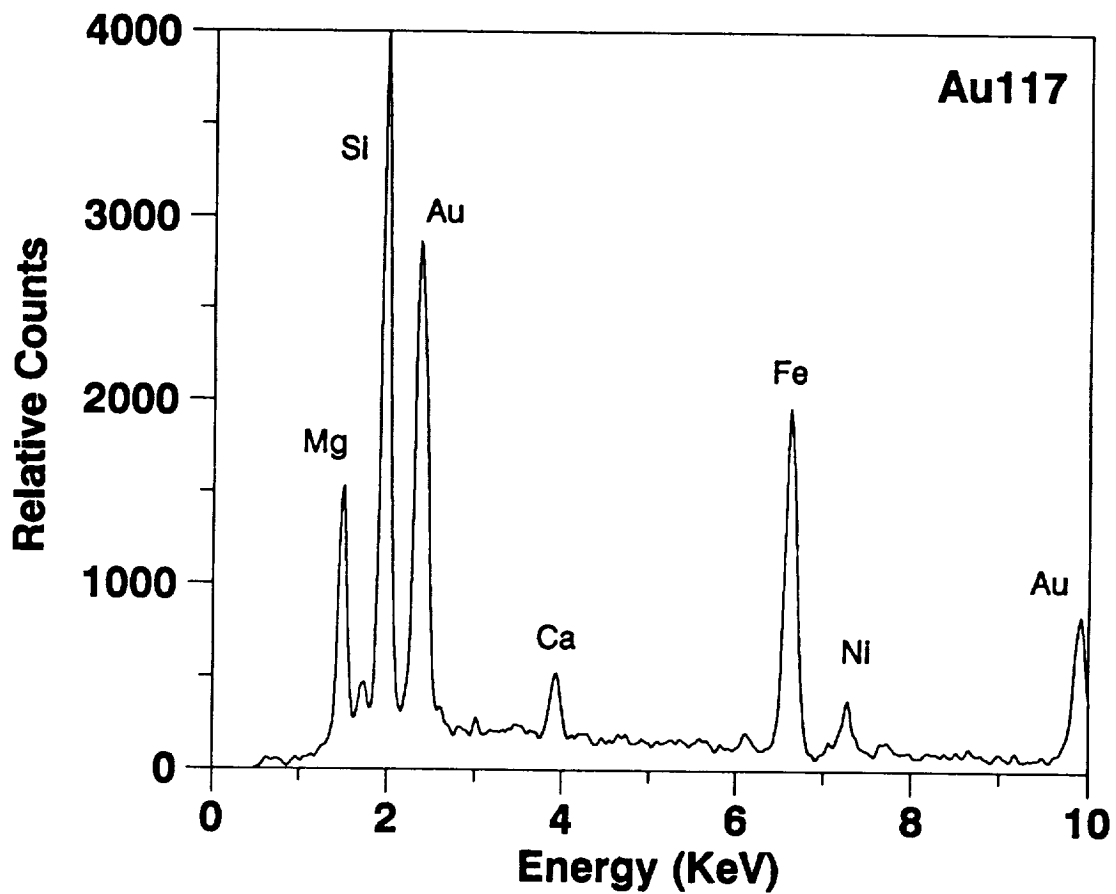
COMPONENT: E00F

FEATURE: 117

CORE: LD-52

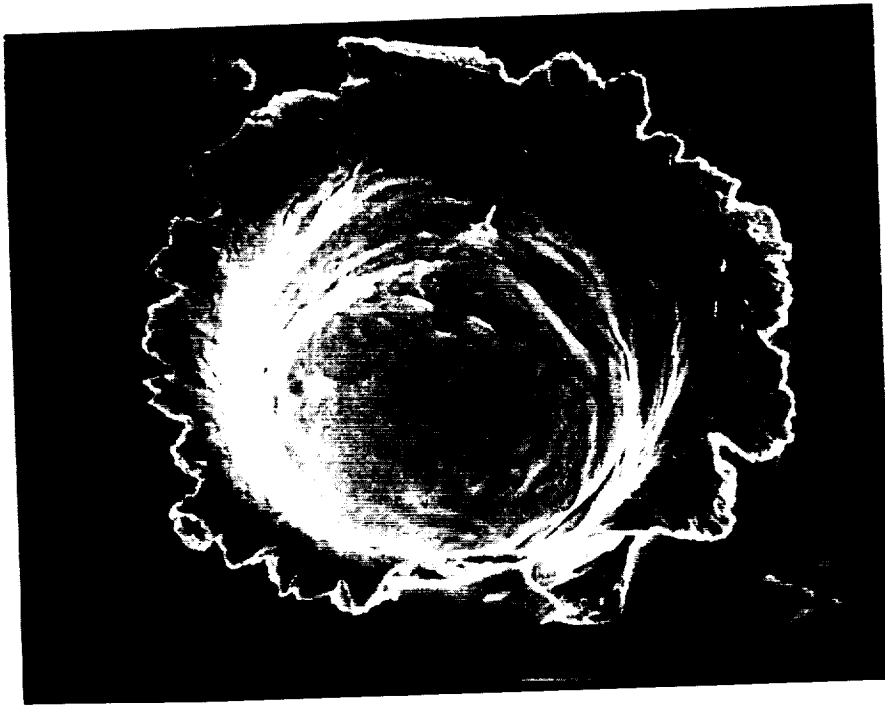
DIAMETER: 20 μ m

ORIGIN: Natural

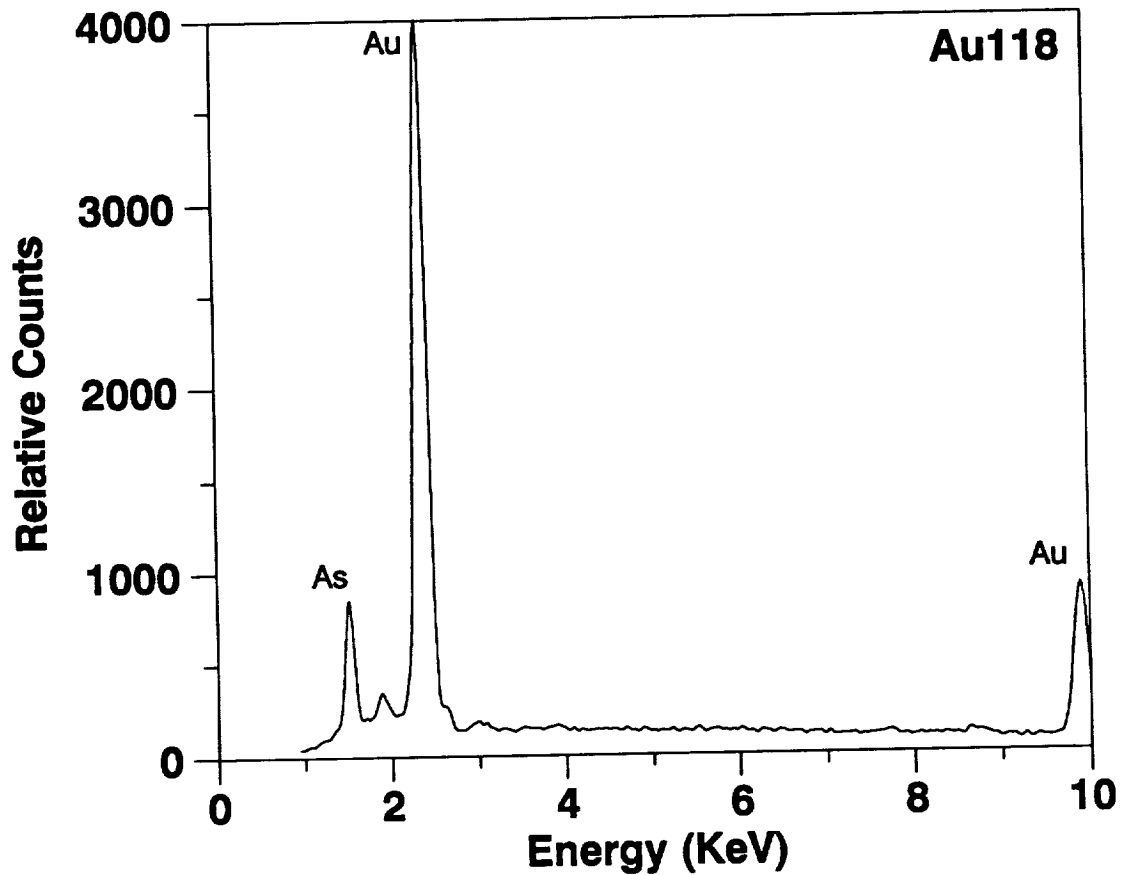


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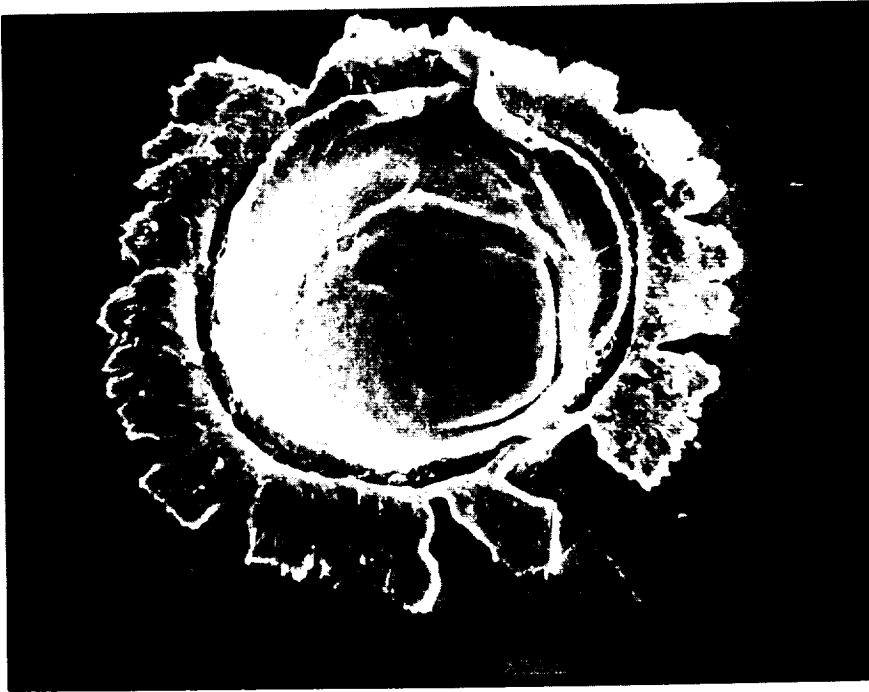


COMPONENT: E00F
FEATURE: 118
CORE: LD-57
DIAMETER: 65 μ m
ORIGIN: Unknown

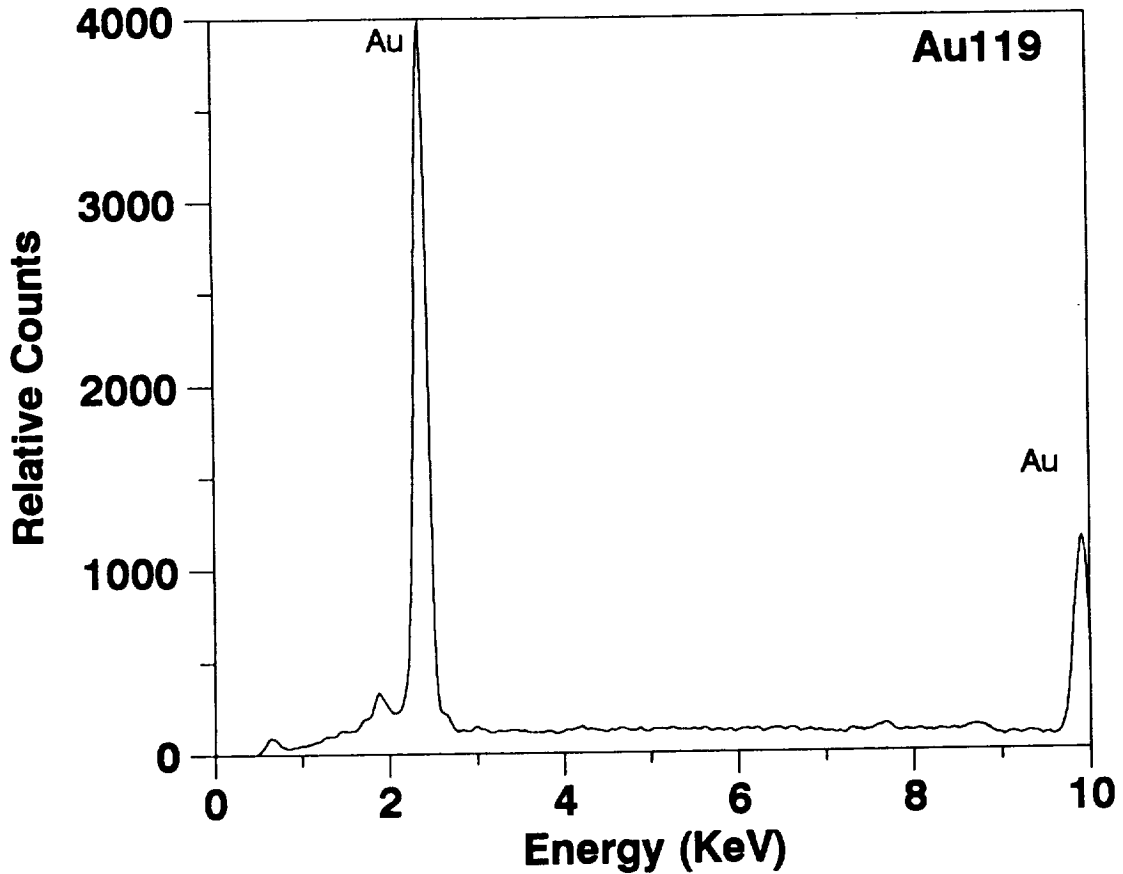


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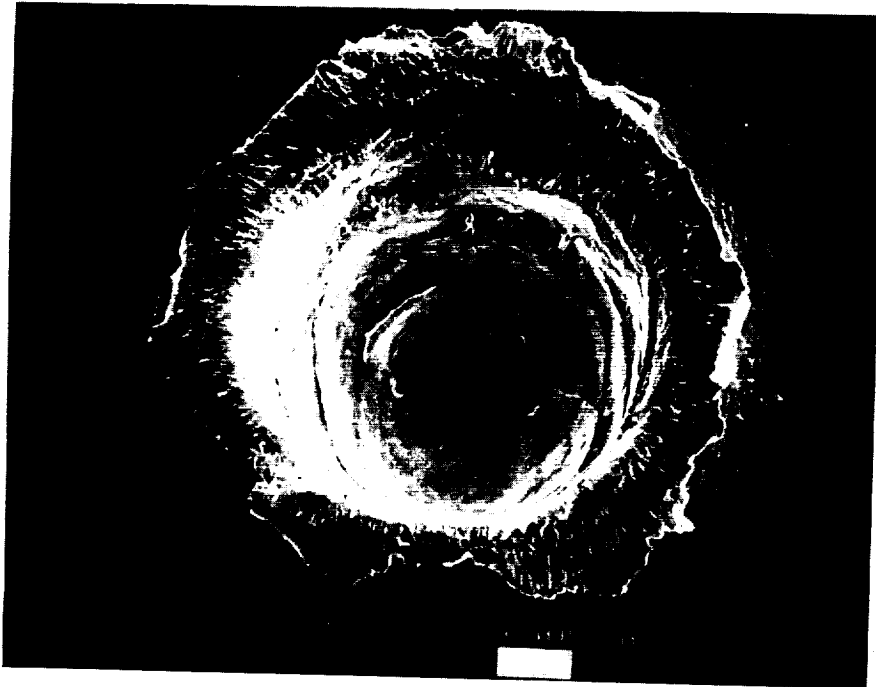


COMPONENT: E00F
FEATURE: 119
CORE: LD-58
DIAMETER: 25 μm
ORIGIN: Unknown

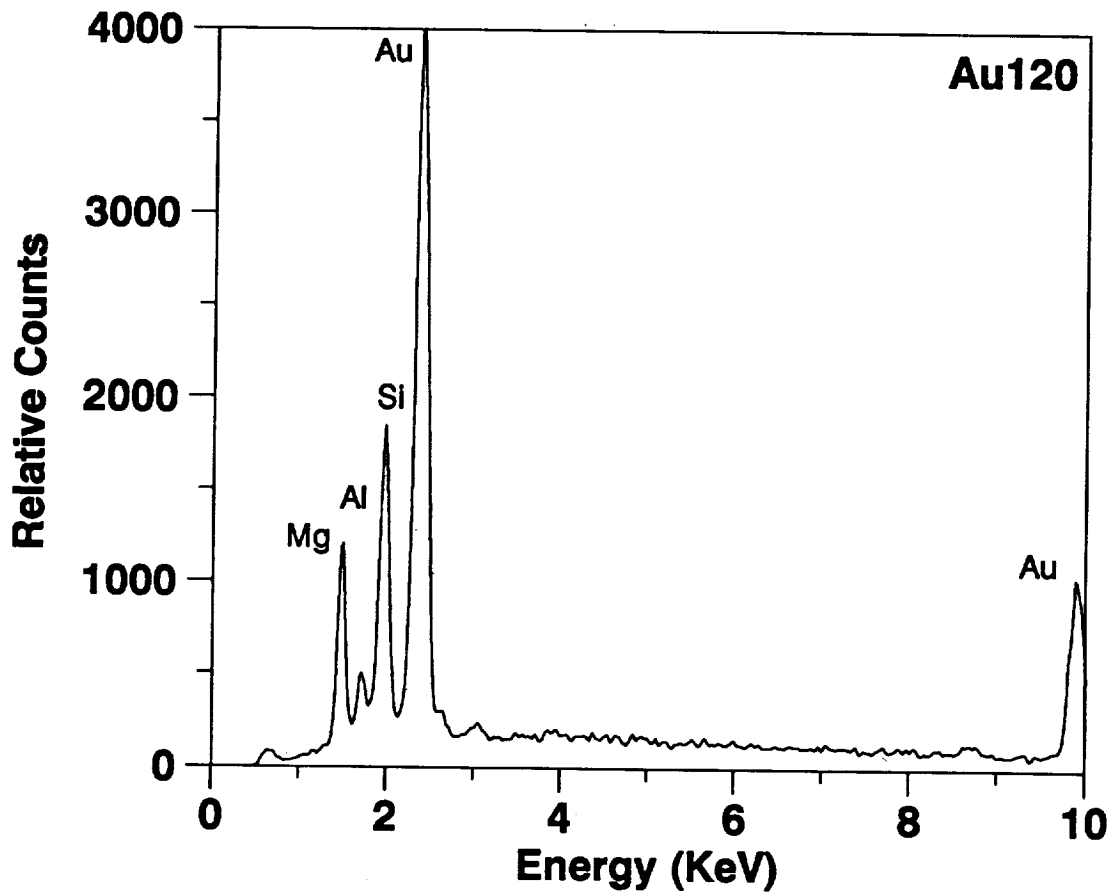


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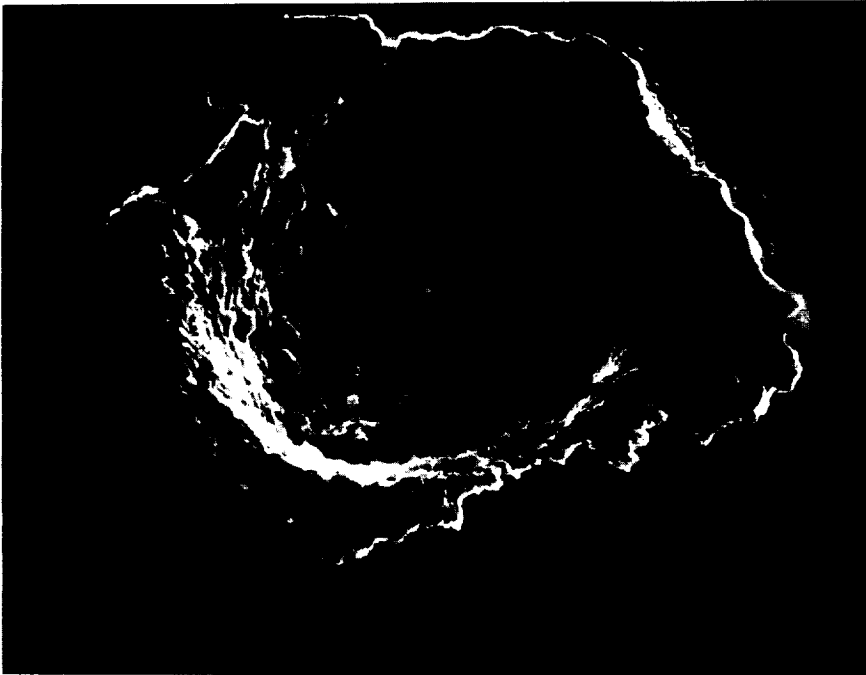


COMPONENT: E00F
FEATURE: 120
CORE: LD-54
DIAMETER: 170 μm
ORIGIN: Natural



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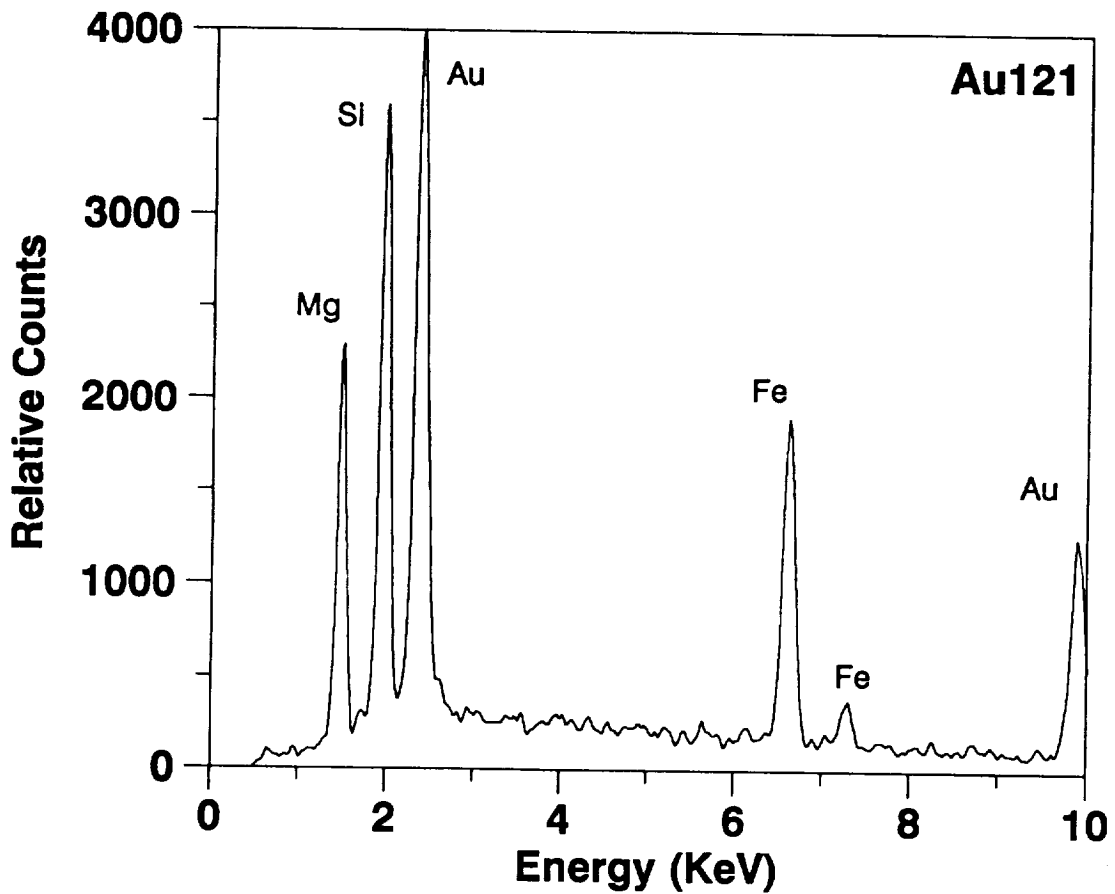
COMPONENT: E00F

FEATURE: 121

CORE: LD-55

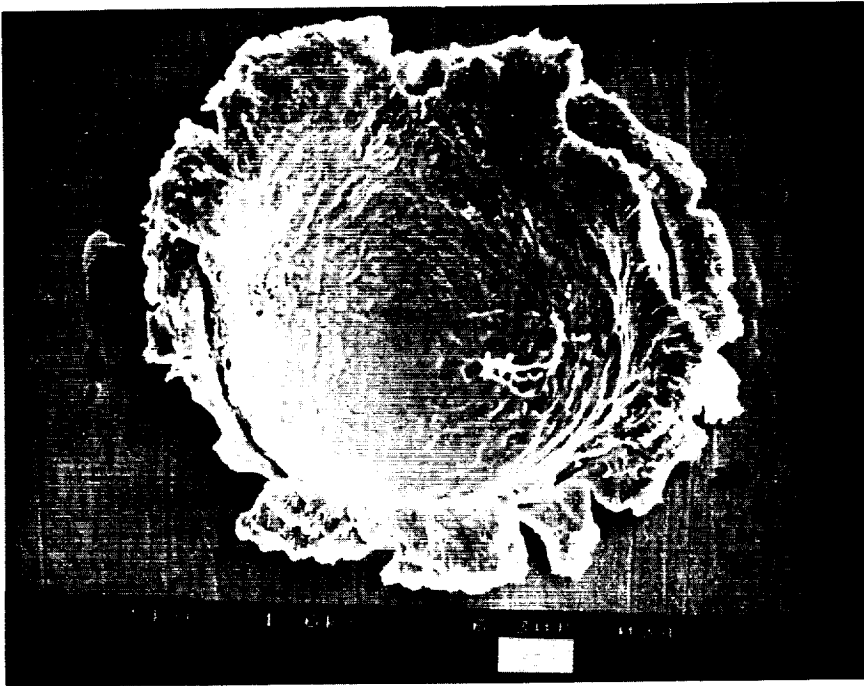
DIAMETER: 40 μ m

ORIGIN: Natural

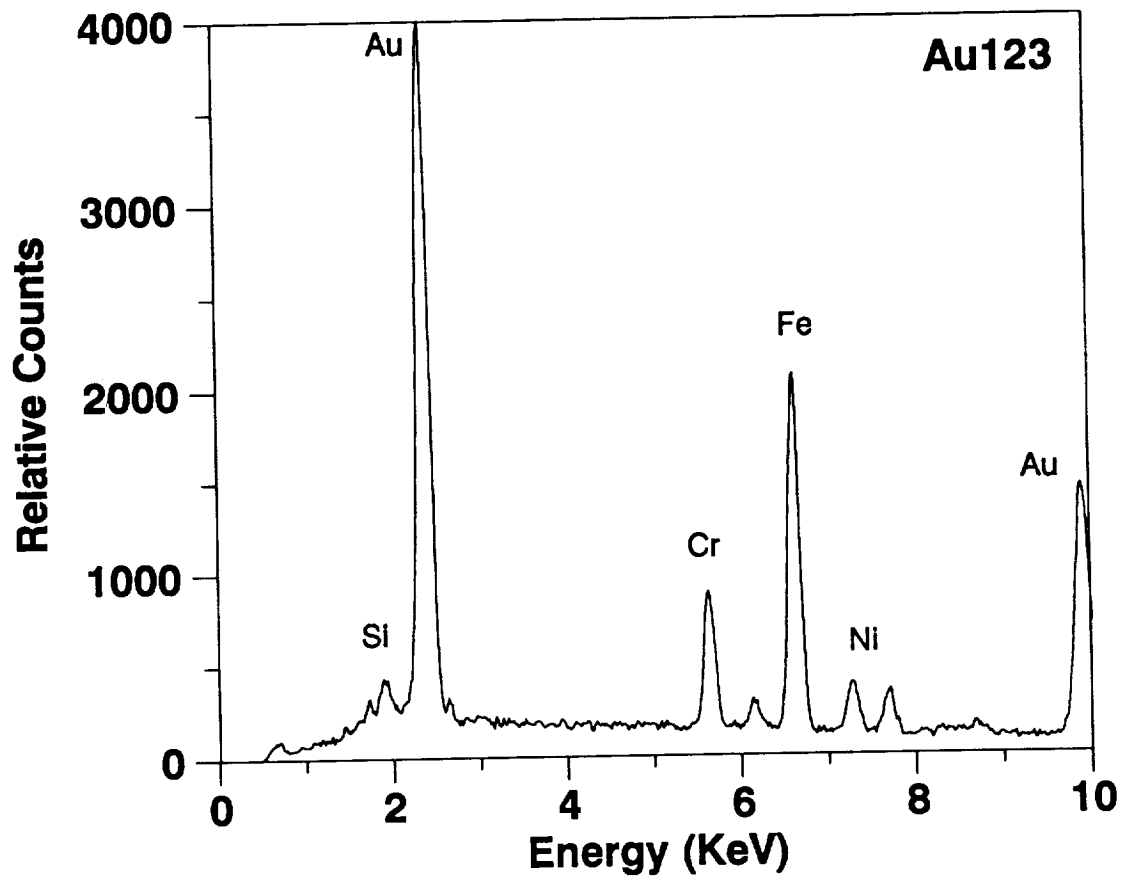


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COMPONENT: E00F
FEATURE: 123
CORE: LD-59
DIAMETER: 35 μ m
ORIGIN: Man-made

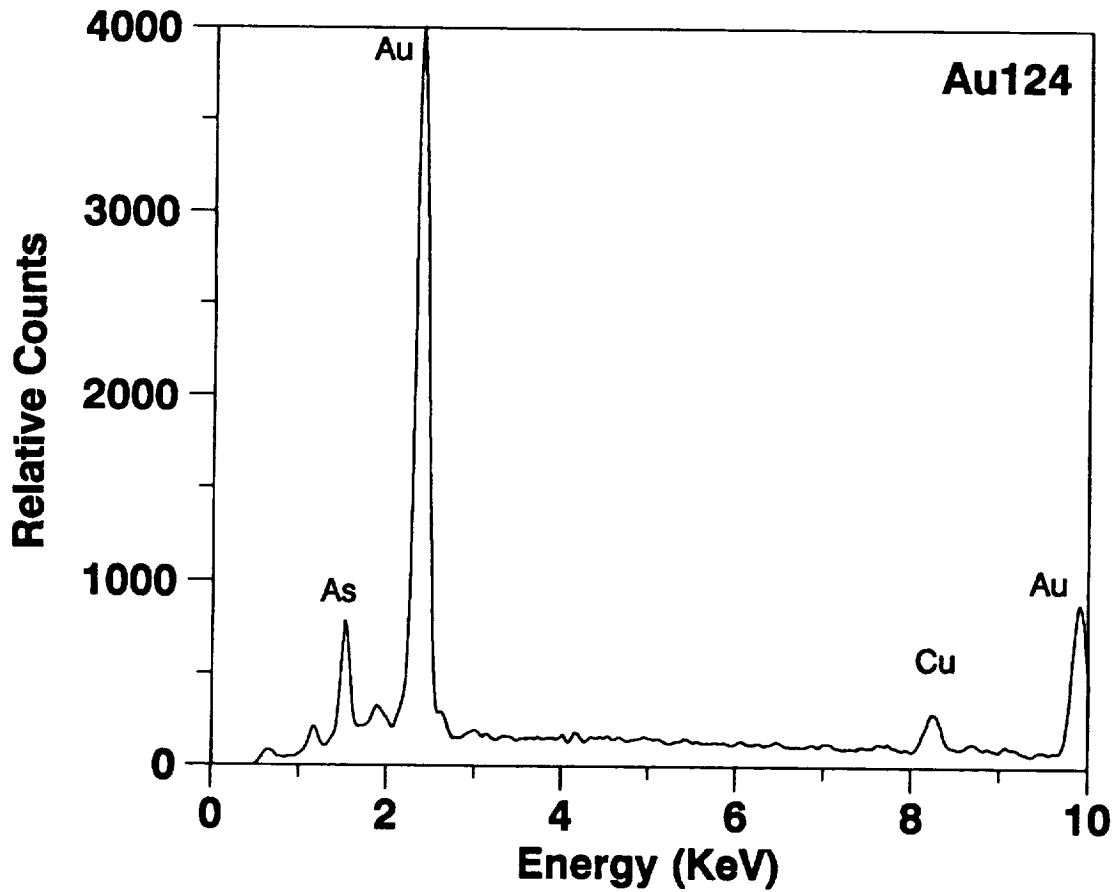


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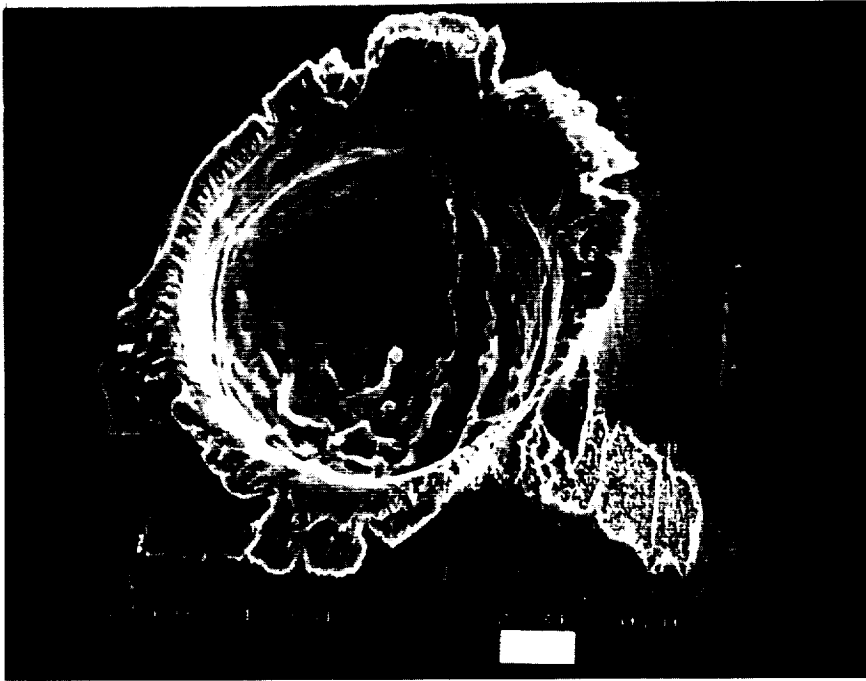


COMPONENT: E00F
FEATURE: 124
CORE: LD-61
DIAMETER: 20 μm
ORIGIN: Unknown

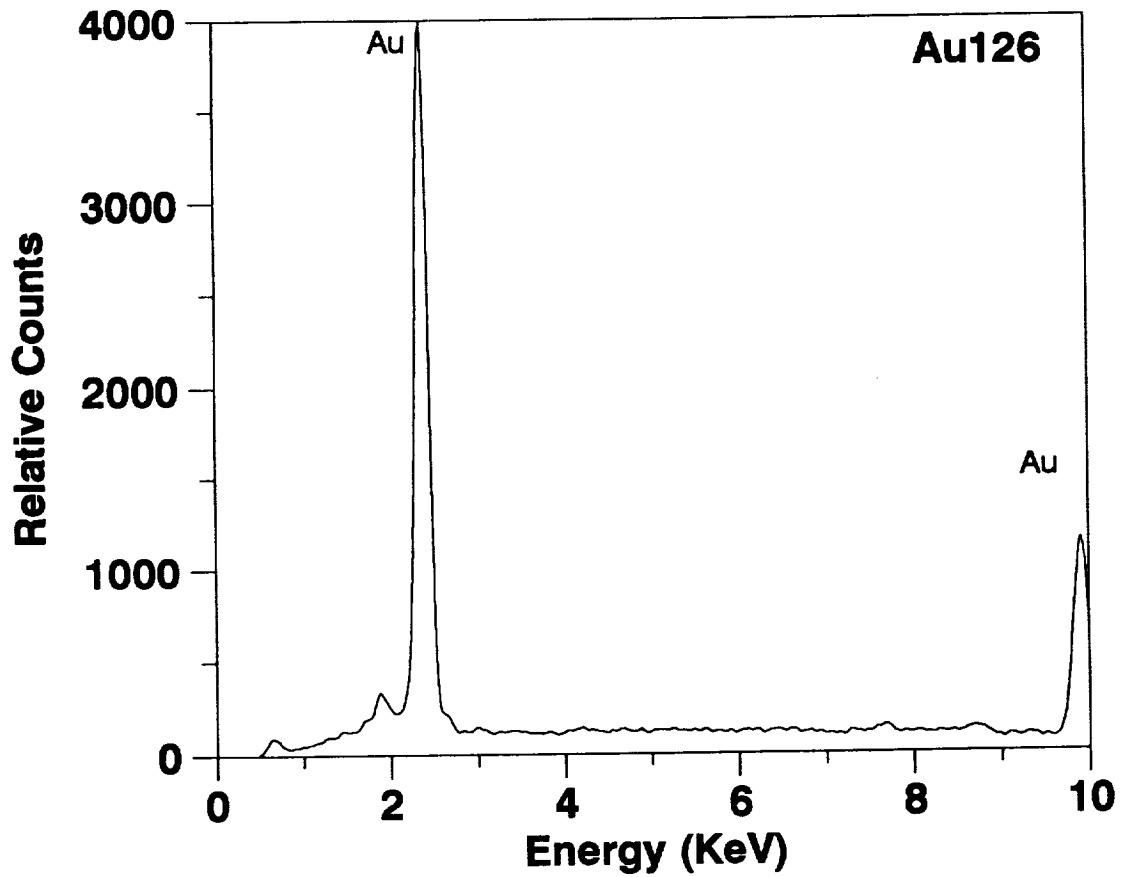


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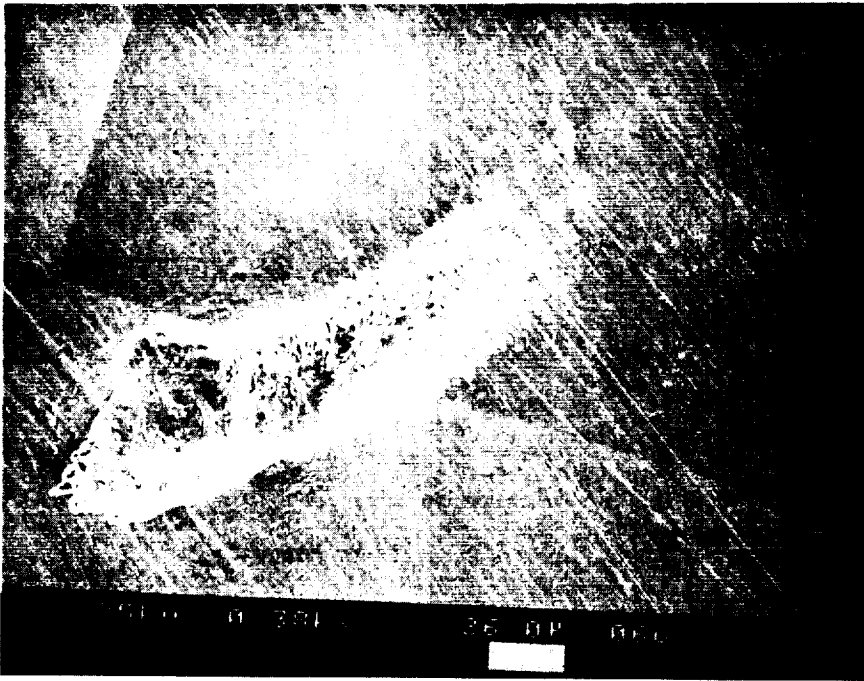


COMPONENT: E00F
FEATURE: 126
CORE: LD-80
DIAMETER: 30 μ m
ORIGIN: Unknown

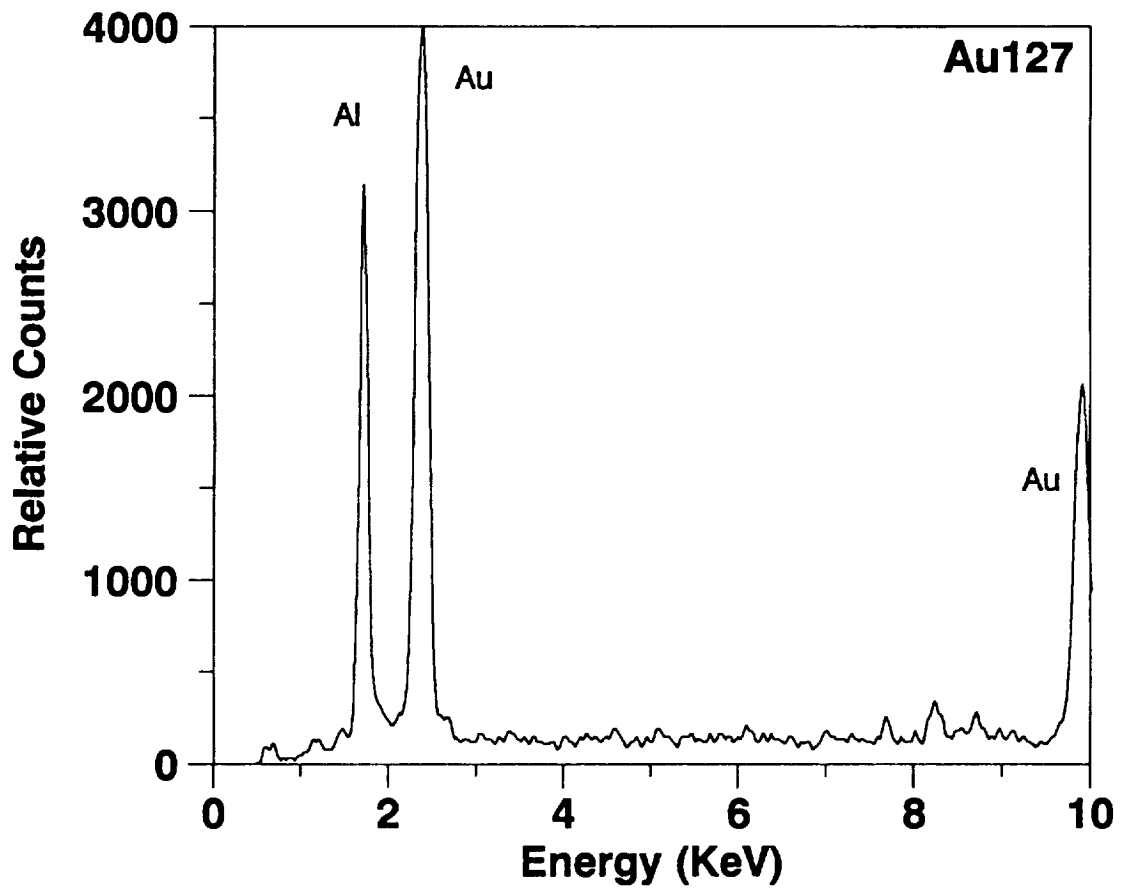


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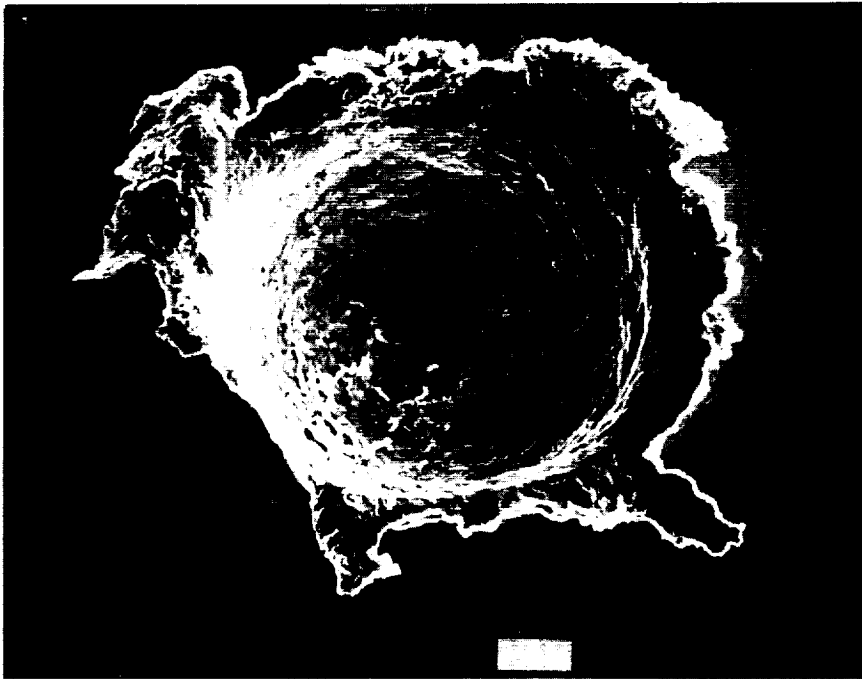


COMPONENT: E00F
FEATURE: 127
CORE: LD-78
DIAMETER: 150 μm
ORIGIN: Man-made

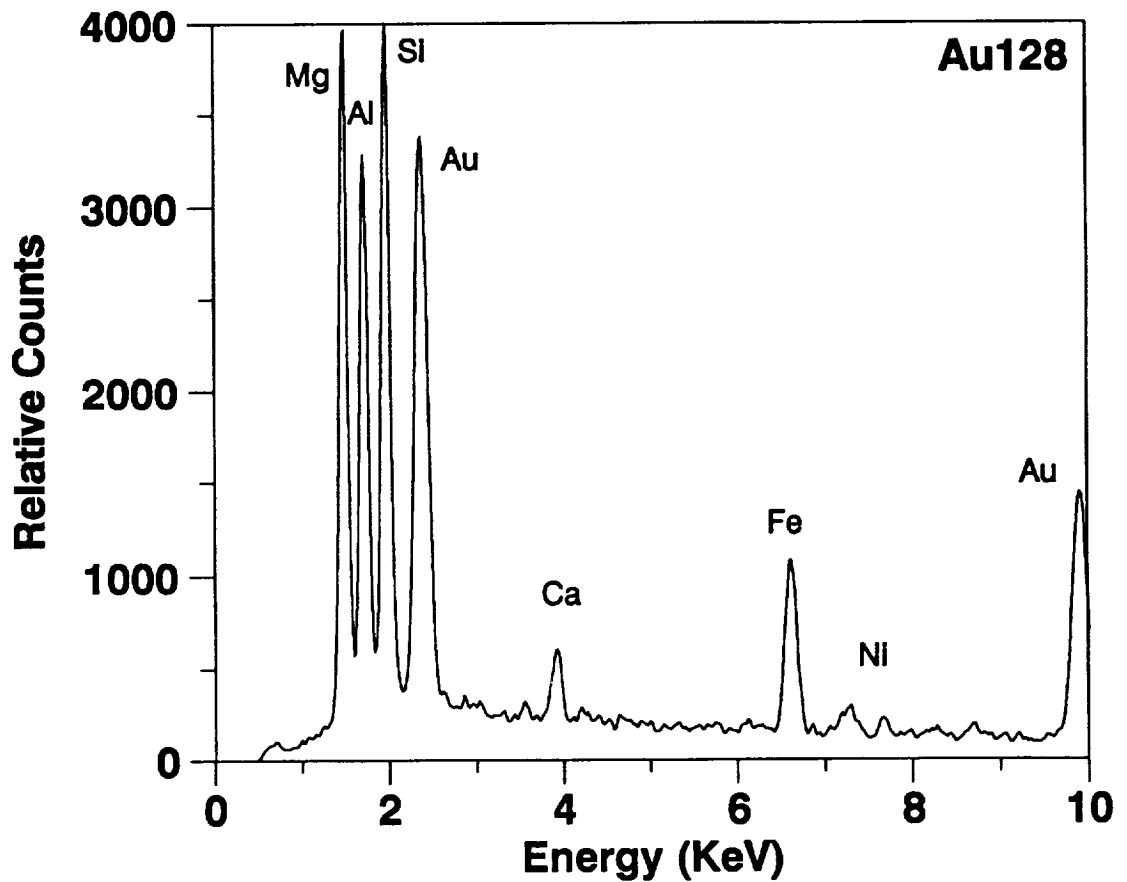


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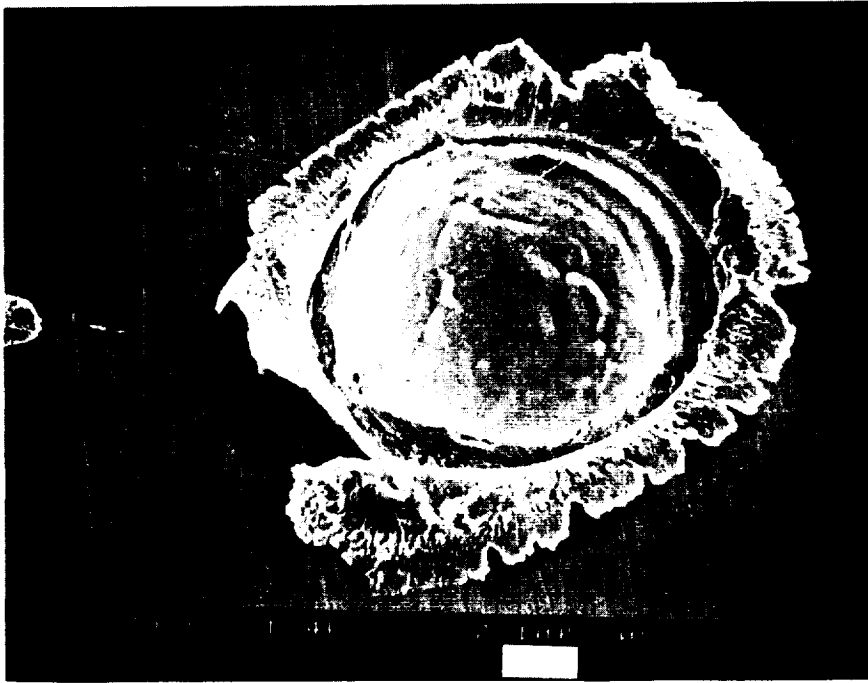


COMPONENT: E00F
FEATURE: 128
CORE: LD-79
DIAMETER: 55 μm
ORIGIN: Natural

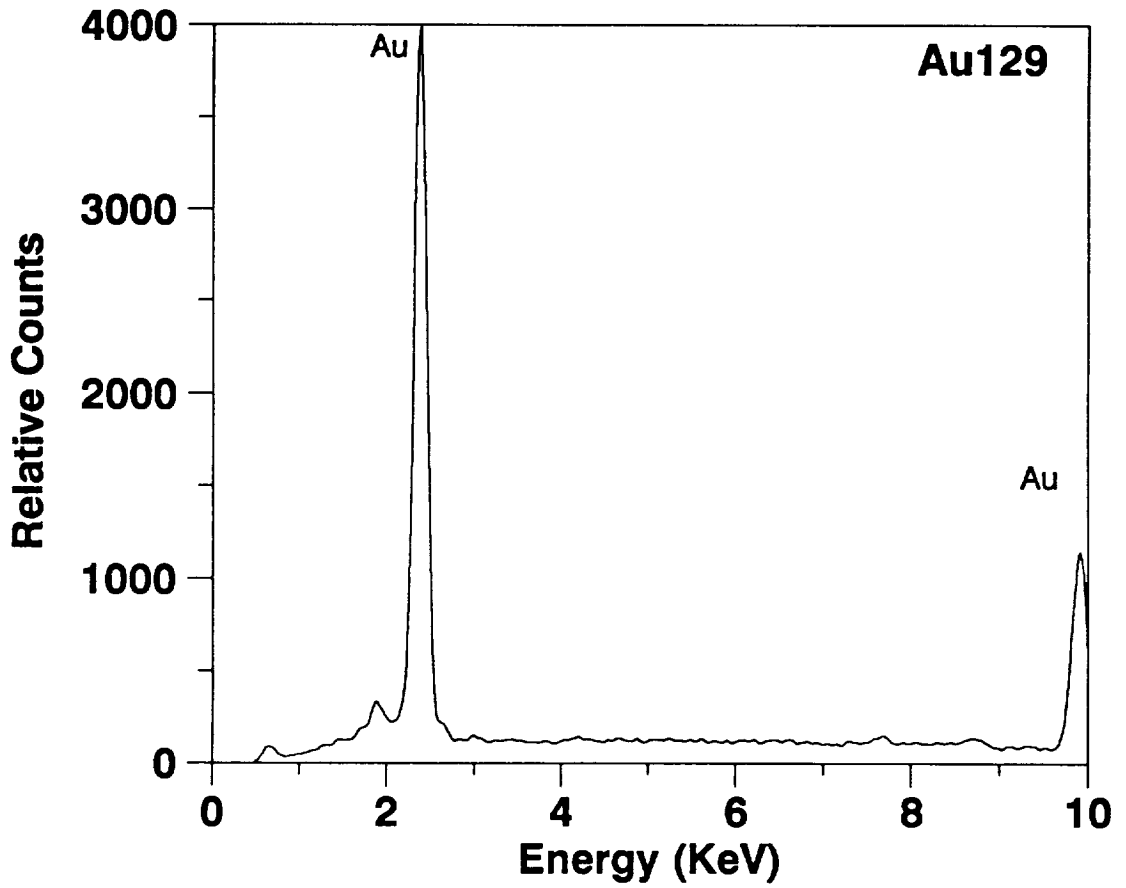


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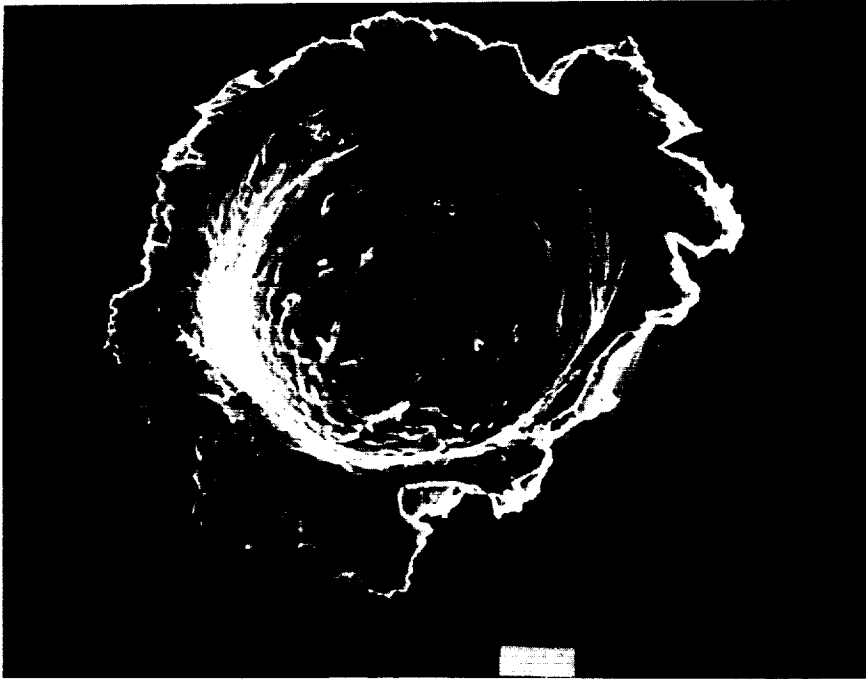


COMPONENT: E00F
FEATURE: 129
CORE: LD-73
DIAMETER: 35 μ m
ORIGIN: Unknown

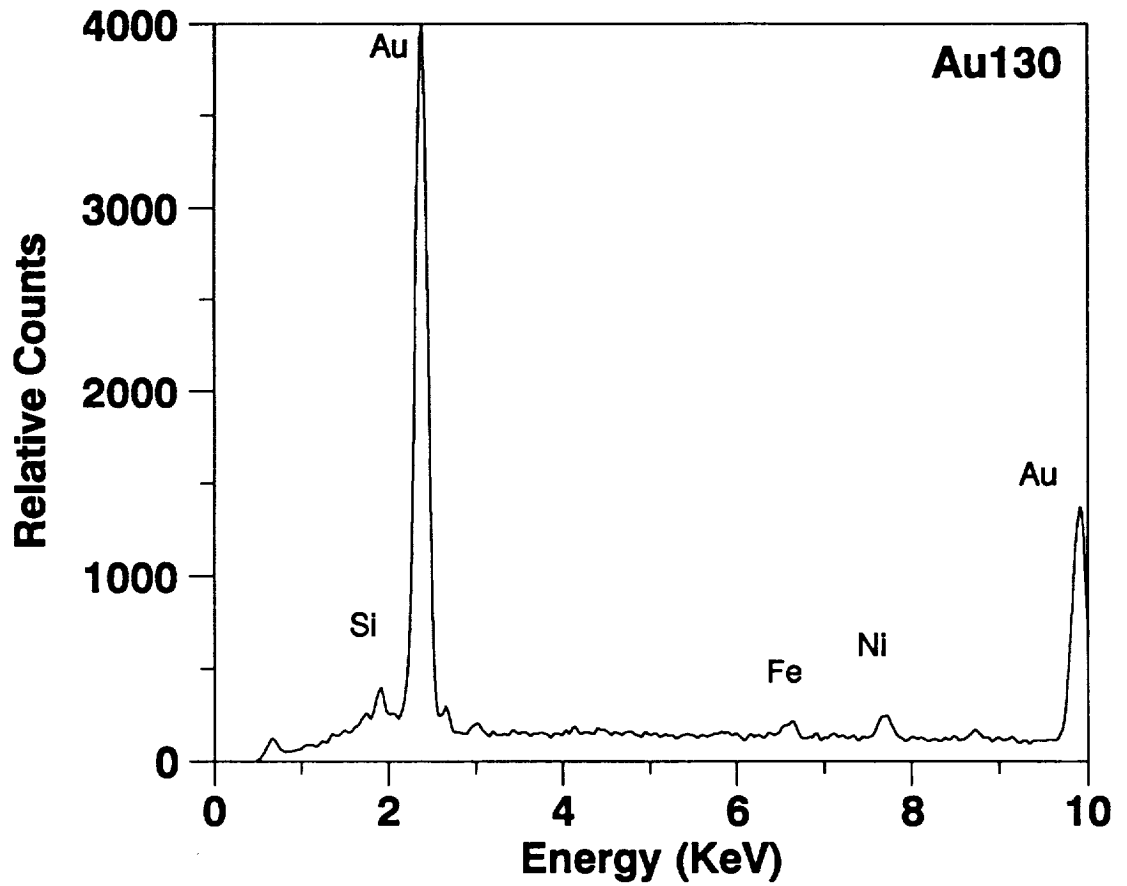


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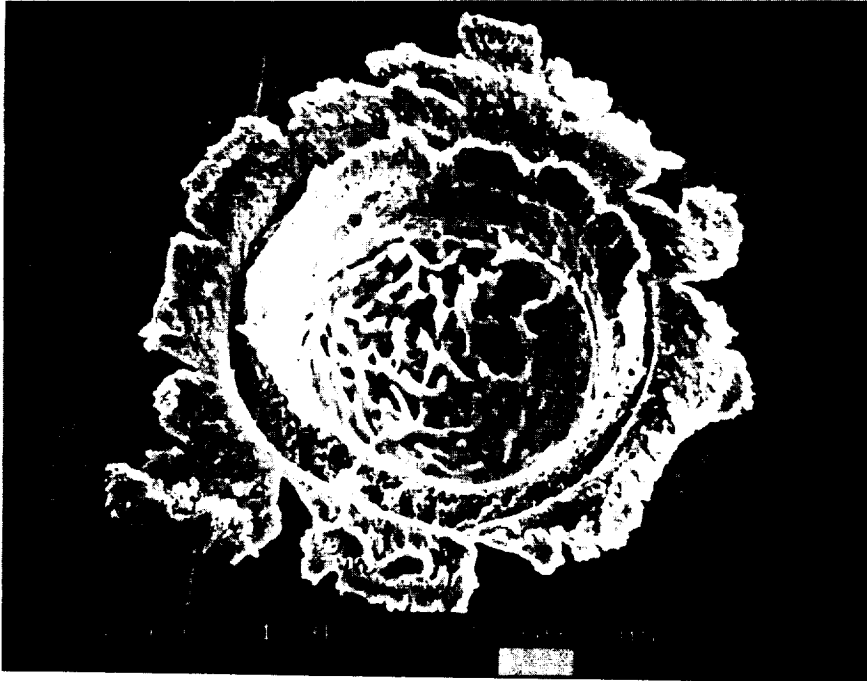


COMPONENT: E00F
FEATURE: 130
CORE: LD-77
DIAMETER: 55 μ m
ORIGIN: Natural



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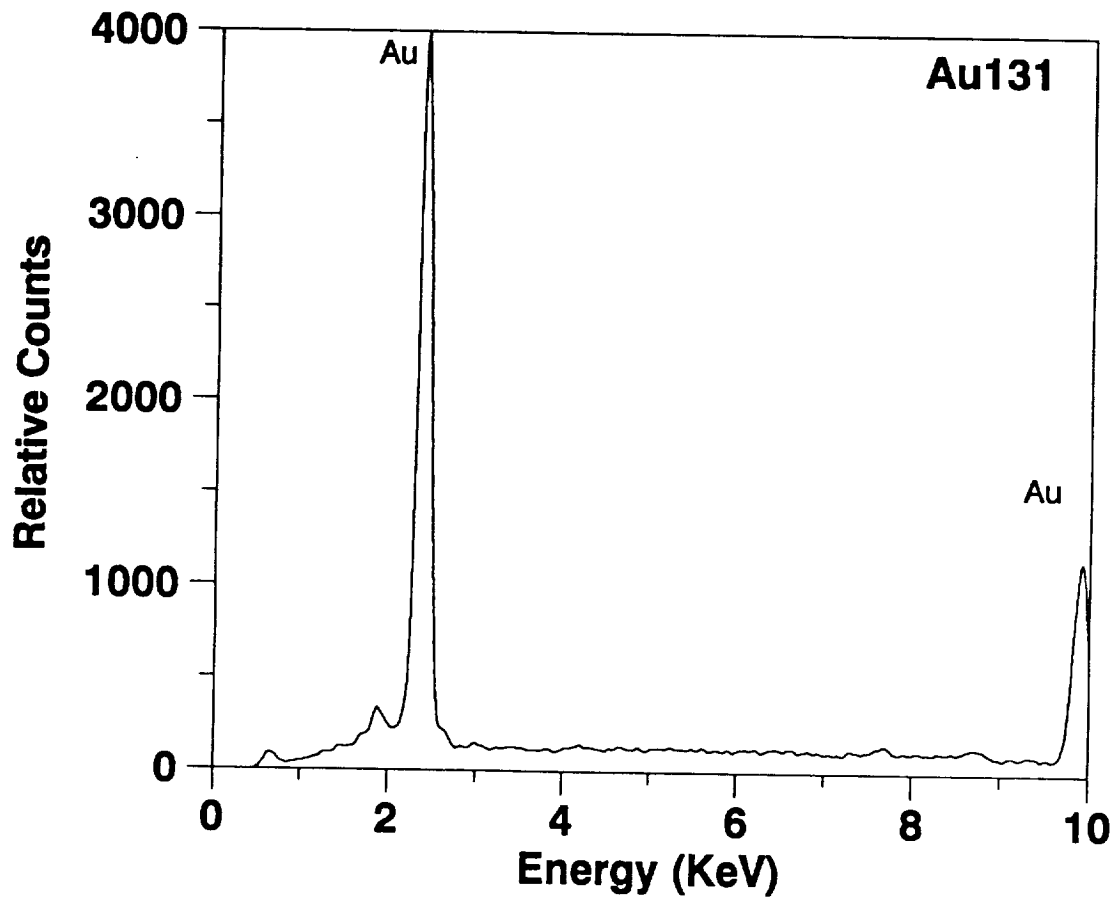
COMPONENT: E00F

FEATURE: 131

CORE: LD-72

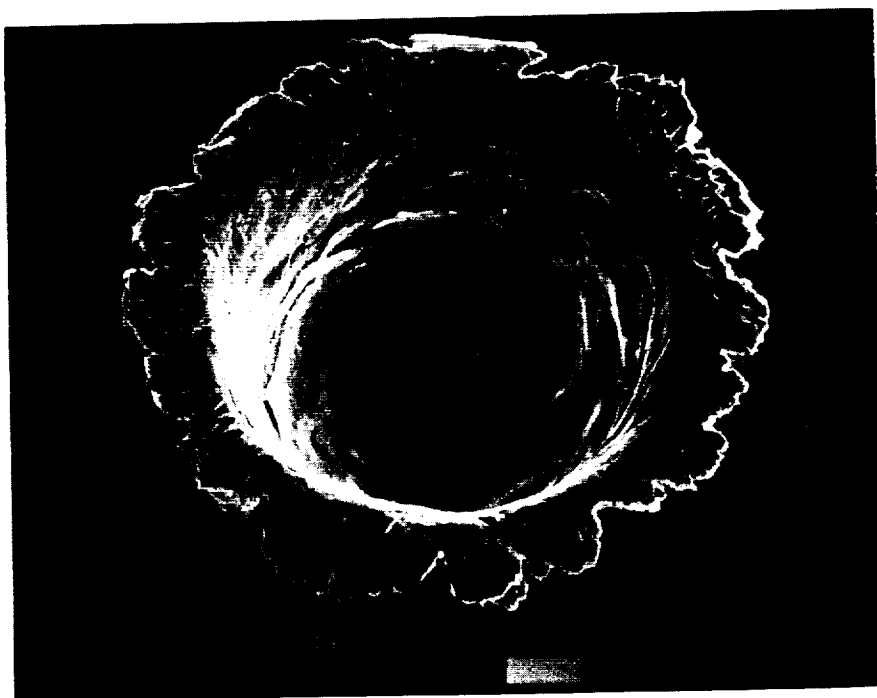
DIAMETER: 25 μ m

ORIGIN: Unknown



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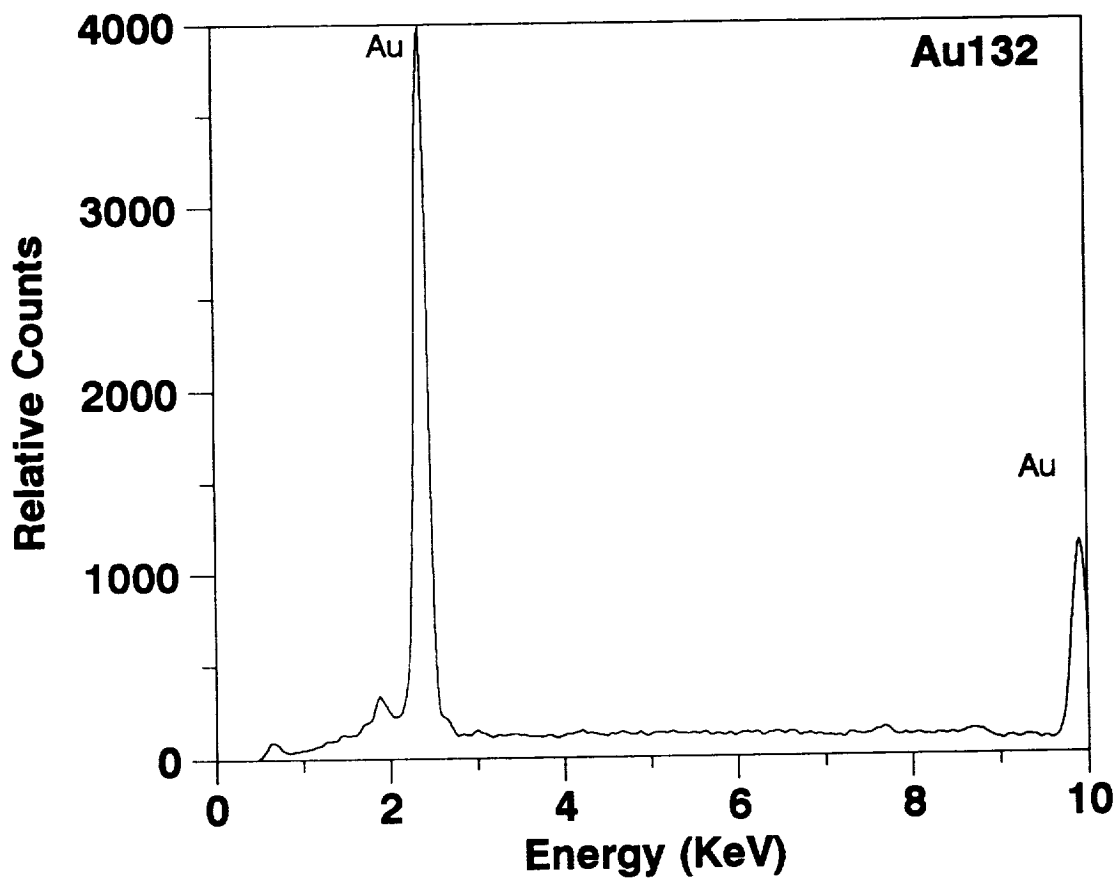
COMPONENT: E00F

FEATURE: 132

CORE: LD-74

DIAMETER: 65 μ m

ORIGIN: Unknown



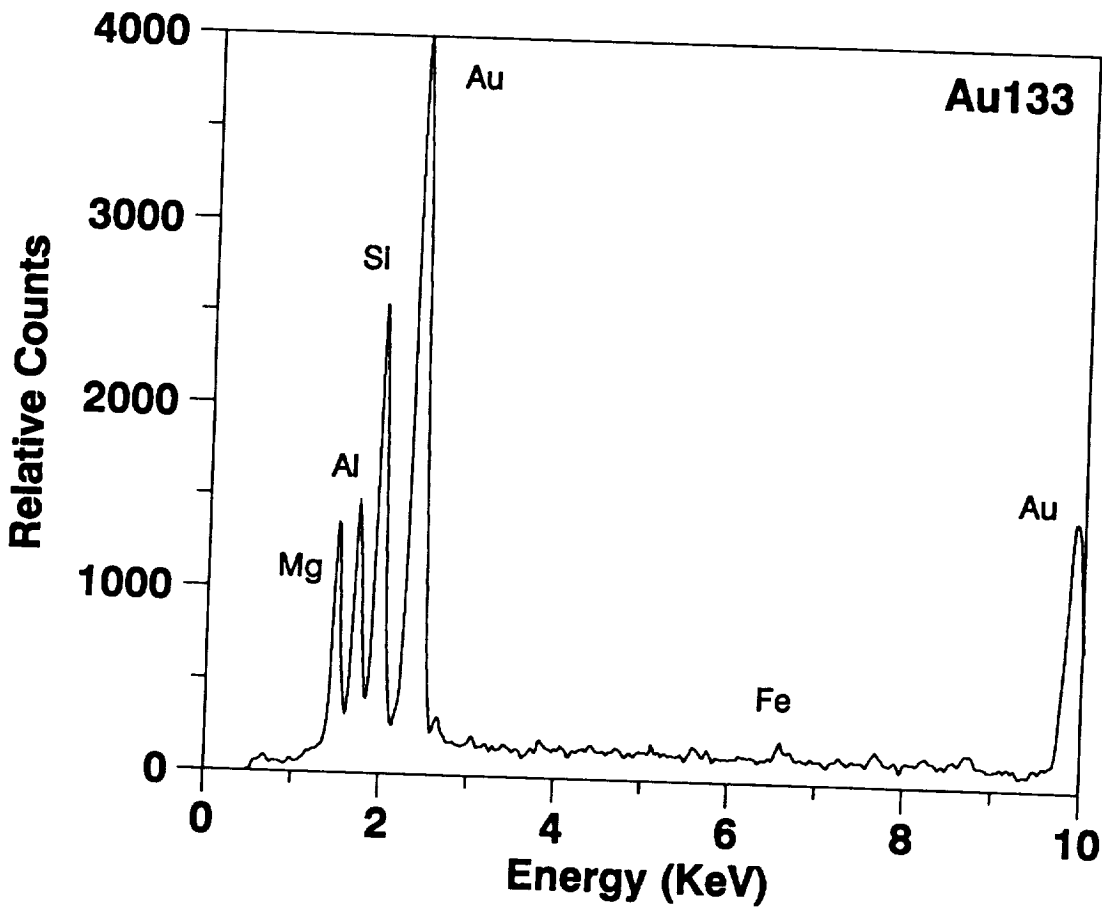
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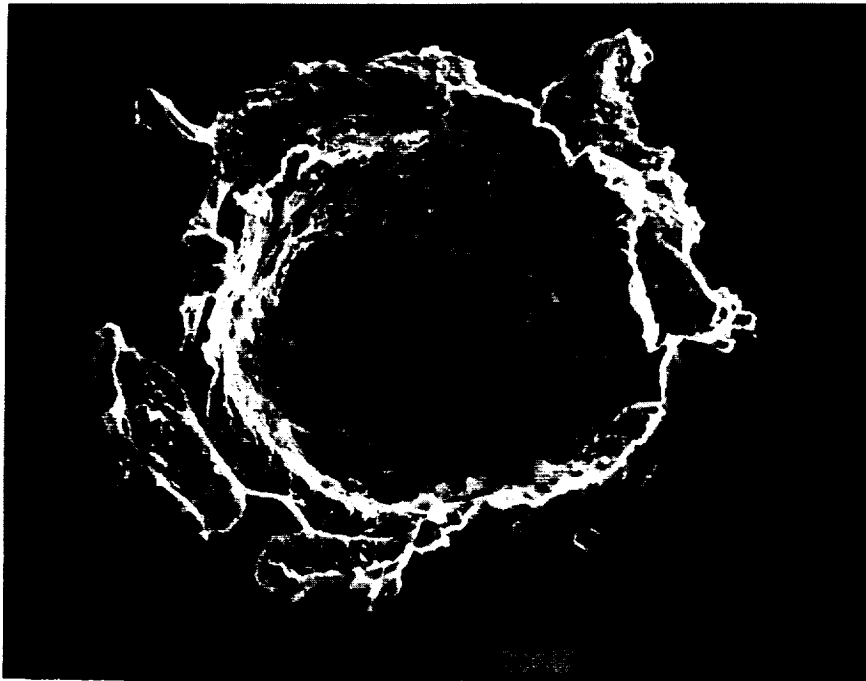
COMPONENT: E00F
FEATURE: 133
CORE: LD-63

DIAMETER: 85 μm
ORIGIN: Natural



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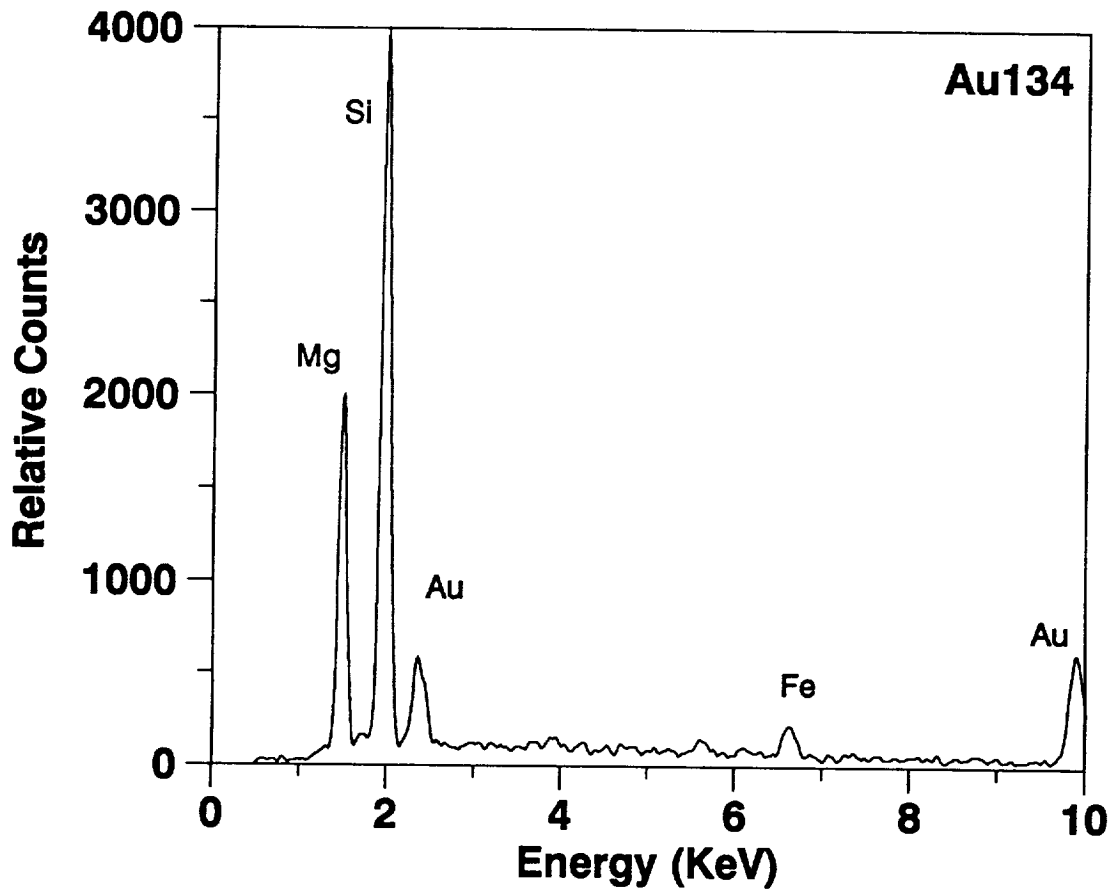
COMPONENT: E00F

FEATURE: 134

CORE: LD-71

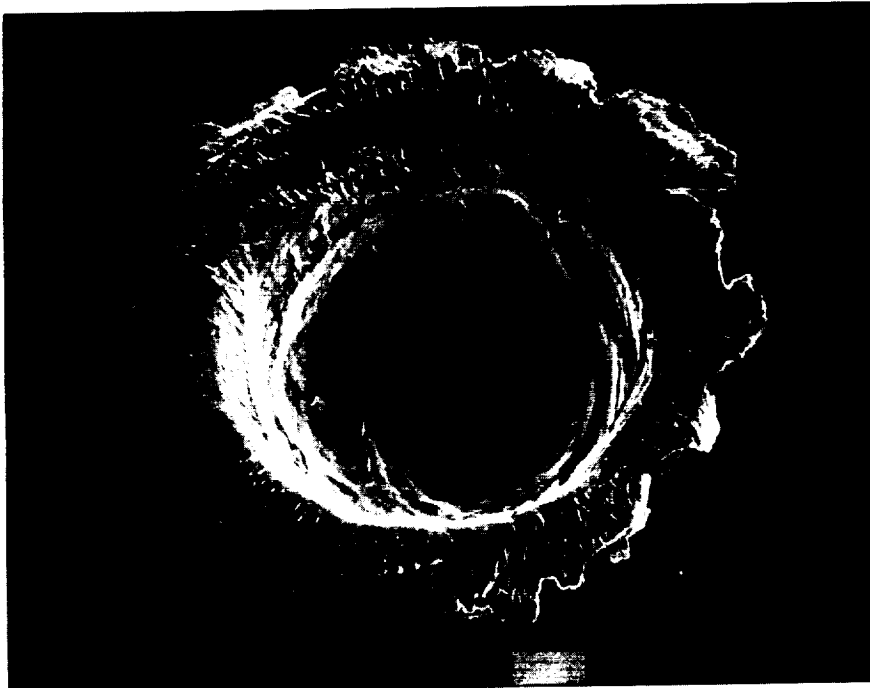
DIAMETER: 55 μm

ORIGIN: Natural

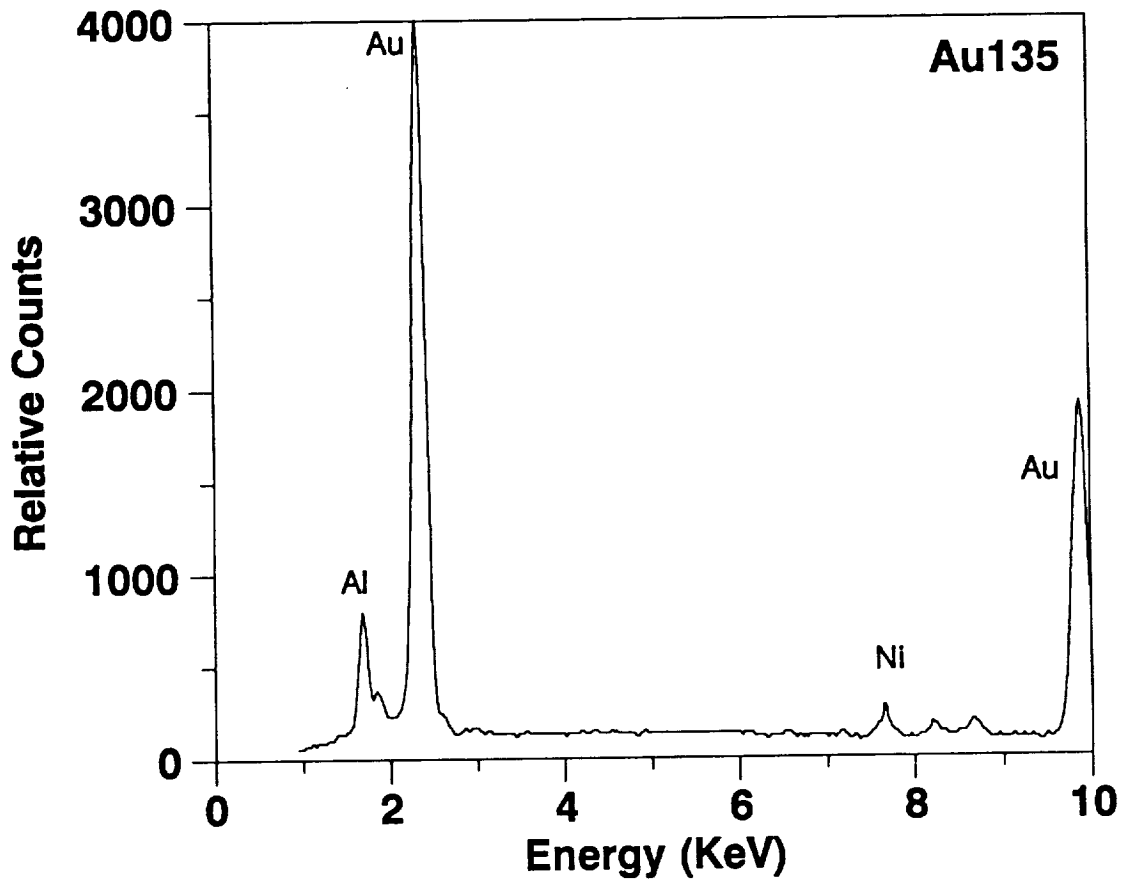


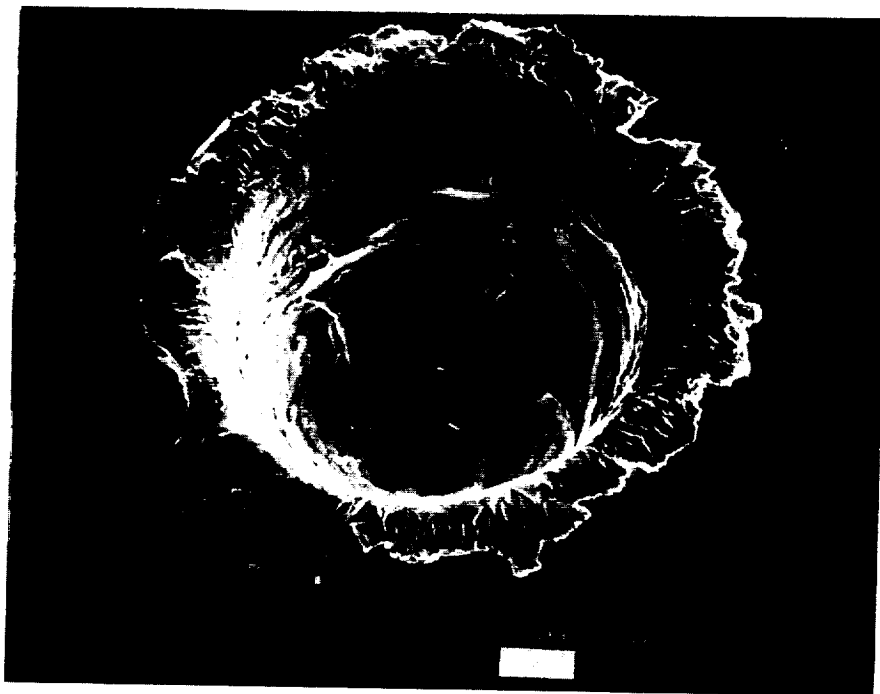
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COMPONENT: E00F
FEATURE: 135
CORE: LD-62
DIAMETER: 160 μ m
ORIGIN: Man-made





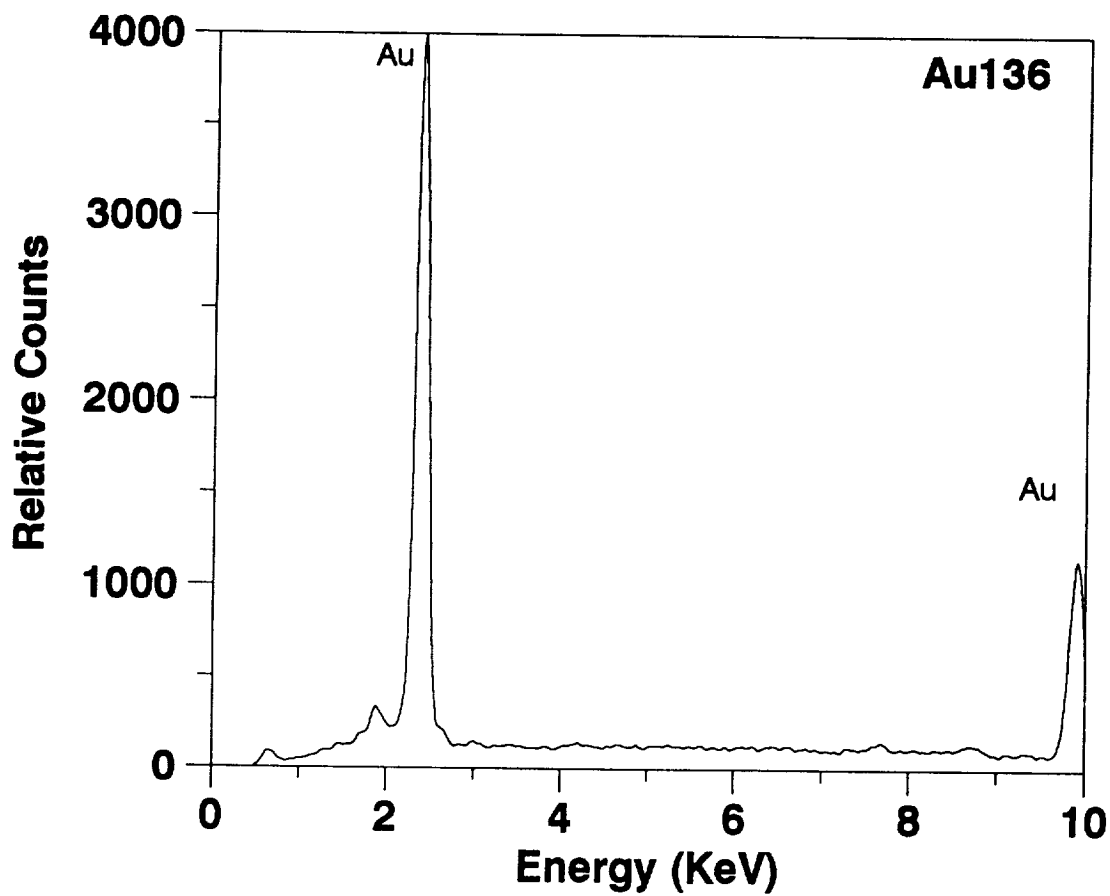
COMPONENT: E00F

FEATURE: 136

CORE: LD-76

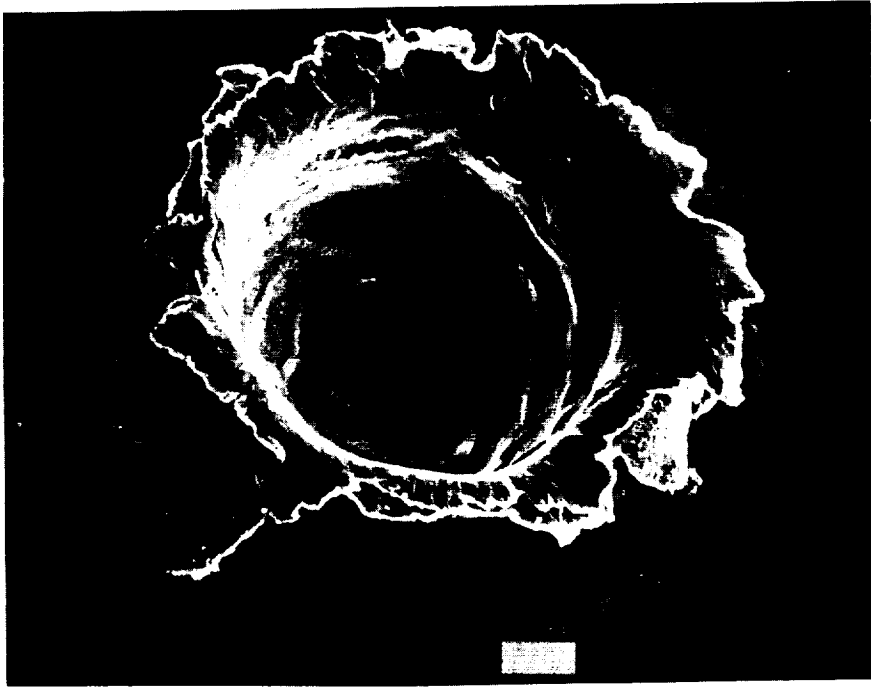
DIAMETER: 105 μm

ORIGIN: Unknown

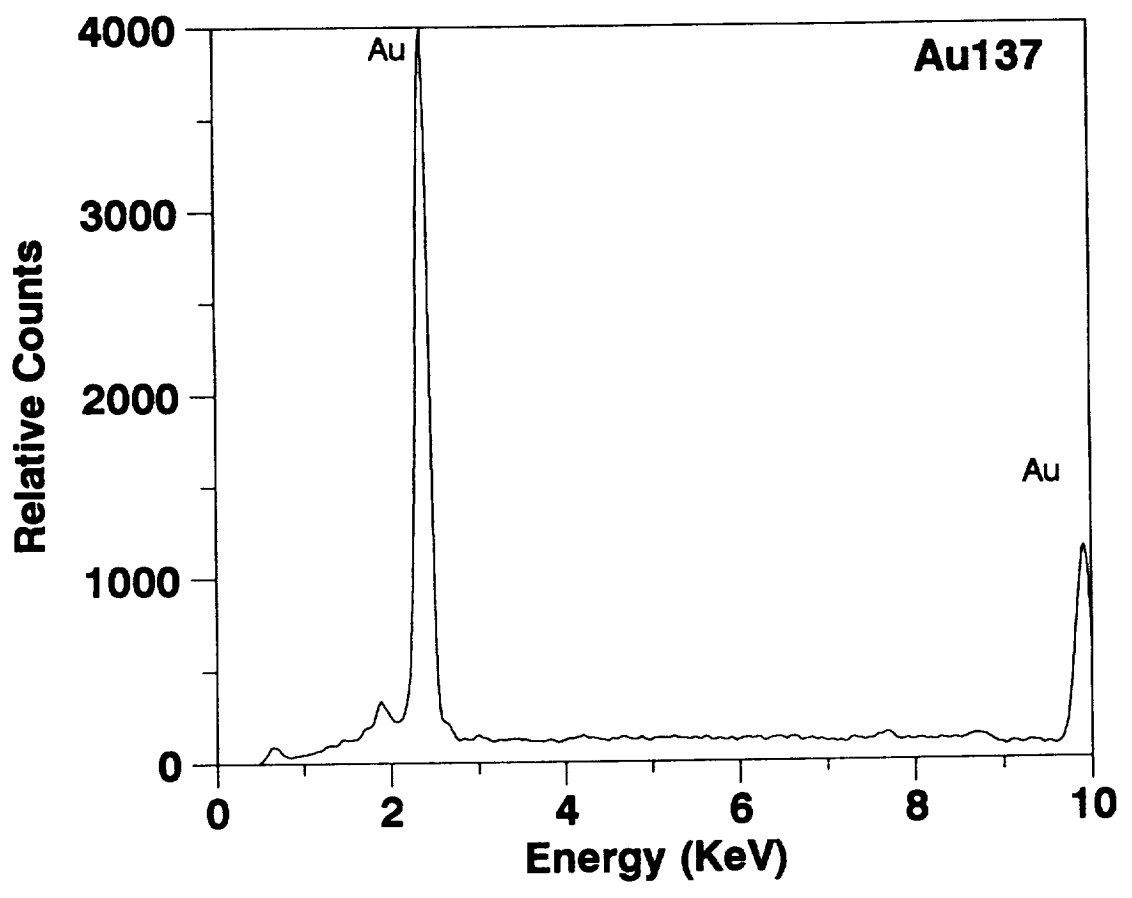


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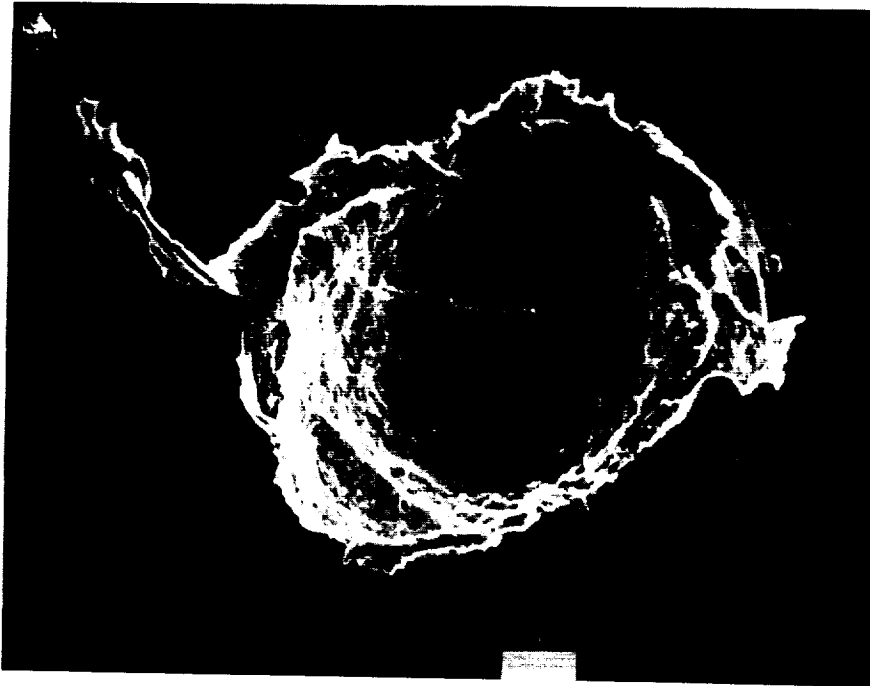


COMPONENT: E00F
FEATURE: 137
CORE: LD-75
DIAMETER: 40 μ m
ORIGIN: Unknown

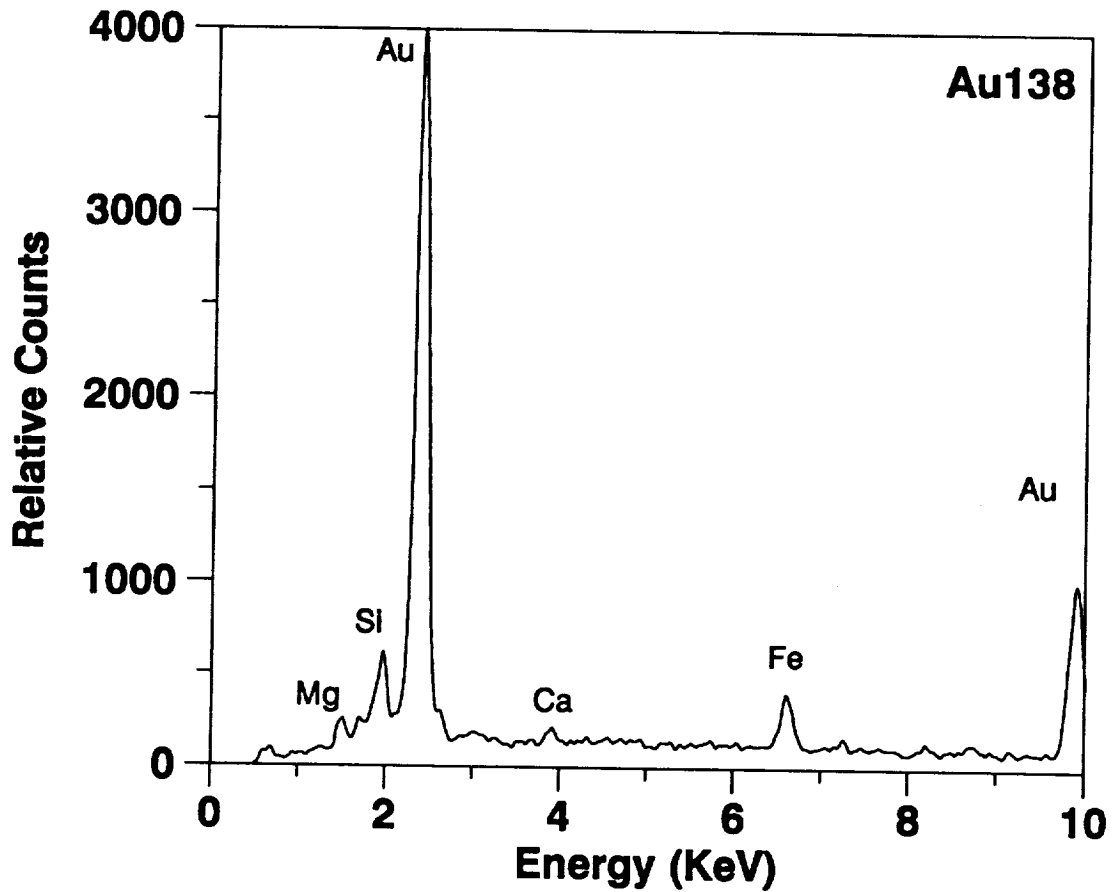


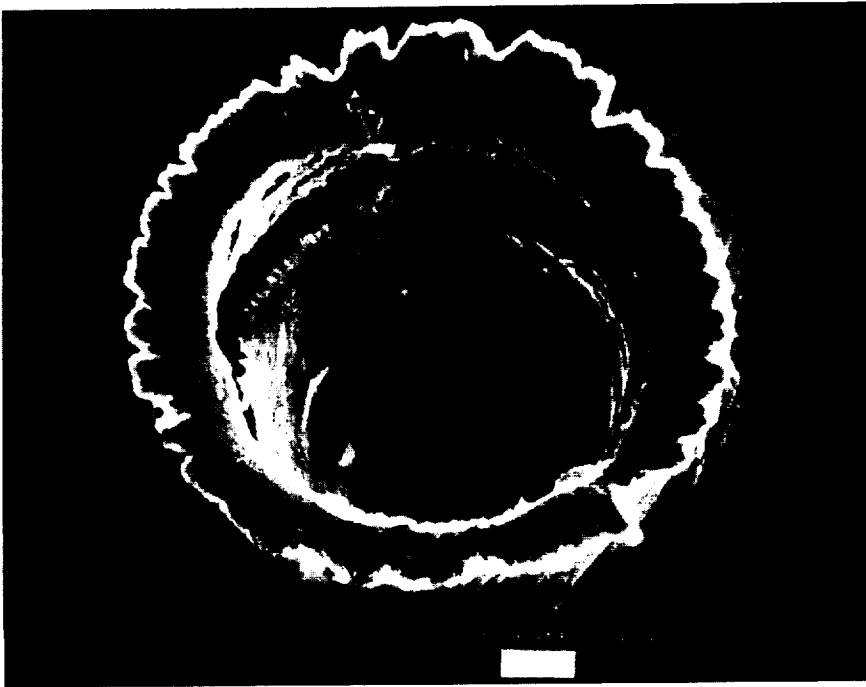
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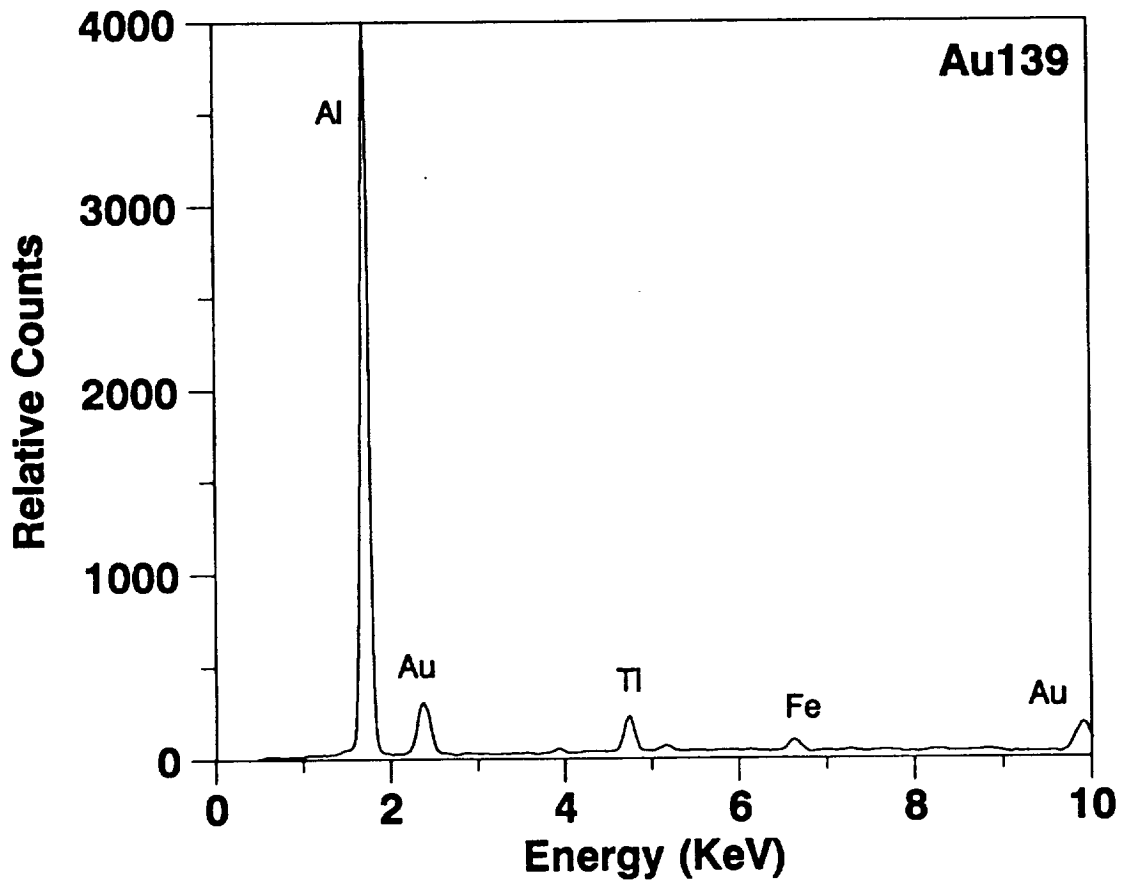


COMPONENT: E00F
FEATURE: 138
CORE: LD-70
DIAMETER: 60 μ m
ORIGIN: Natural



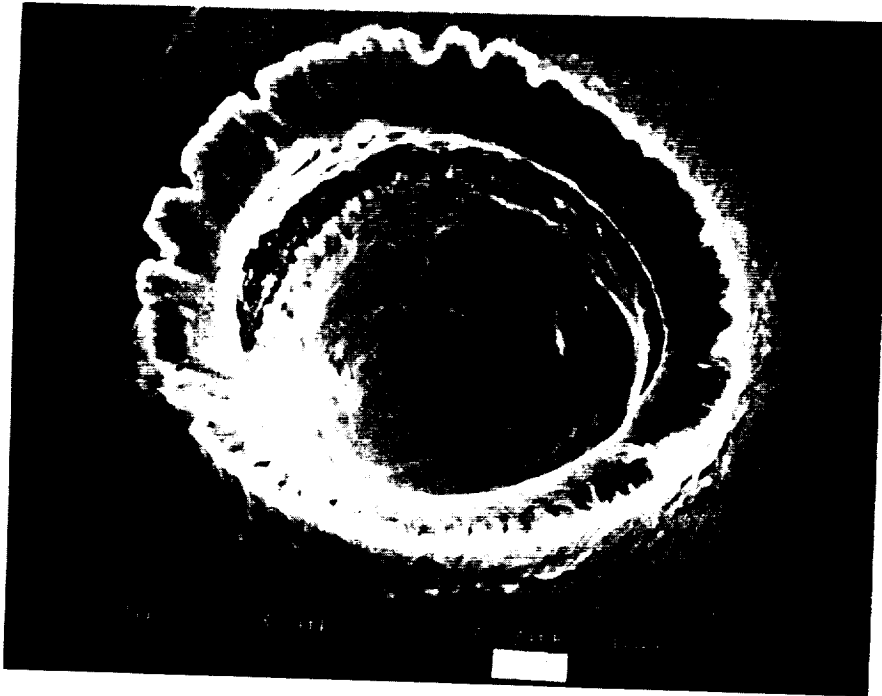


COMPONENT: E00F
FEATURE: 139
CORE: LD-64
DIAMETER: 15 μm
ORIGIN: Man-made

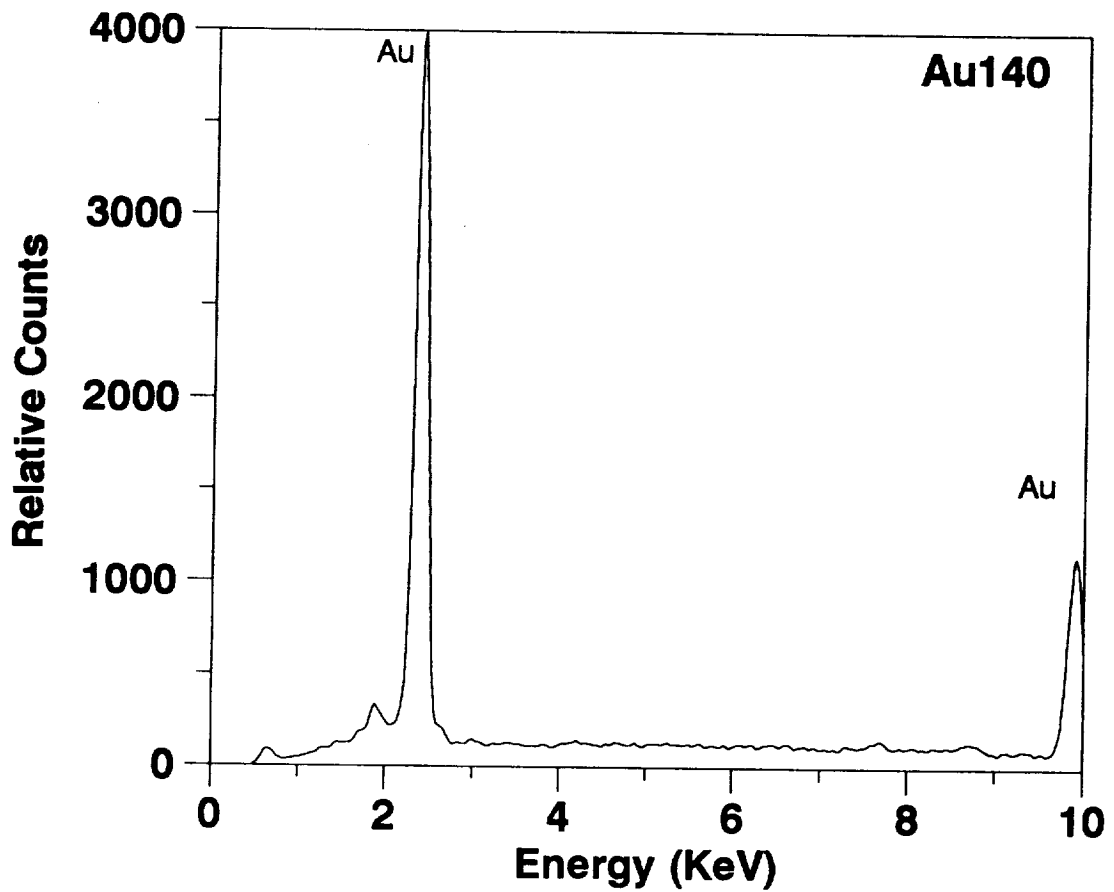


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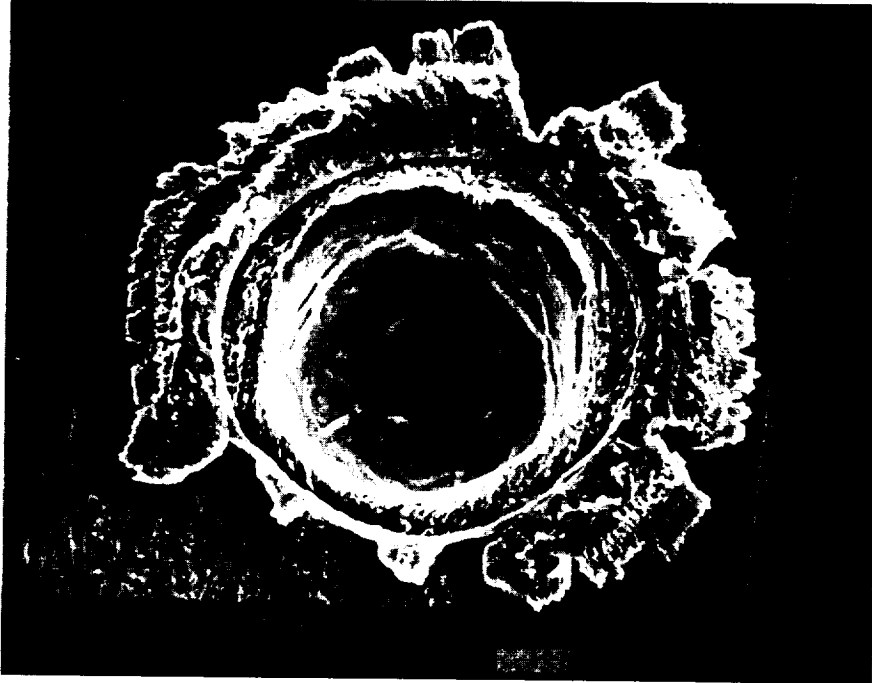


COMPONENT: EEOF
FEATURE: 140
CORE: LD-65
DIAMETER: 10 μm
ORIGIN: Unknown



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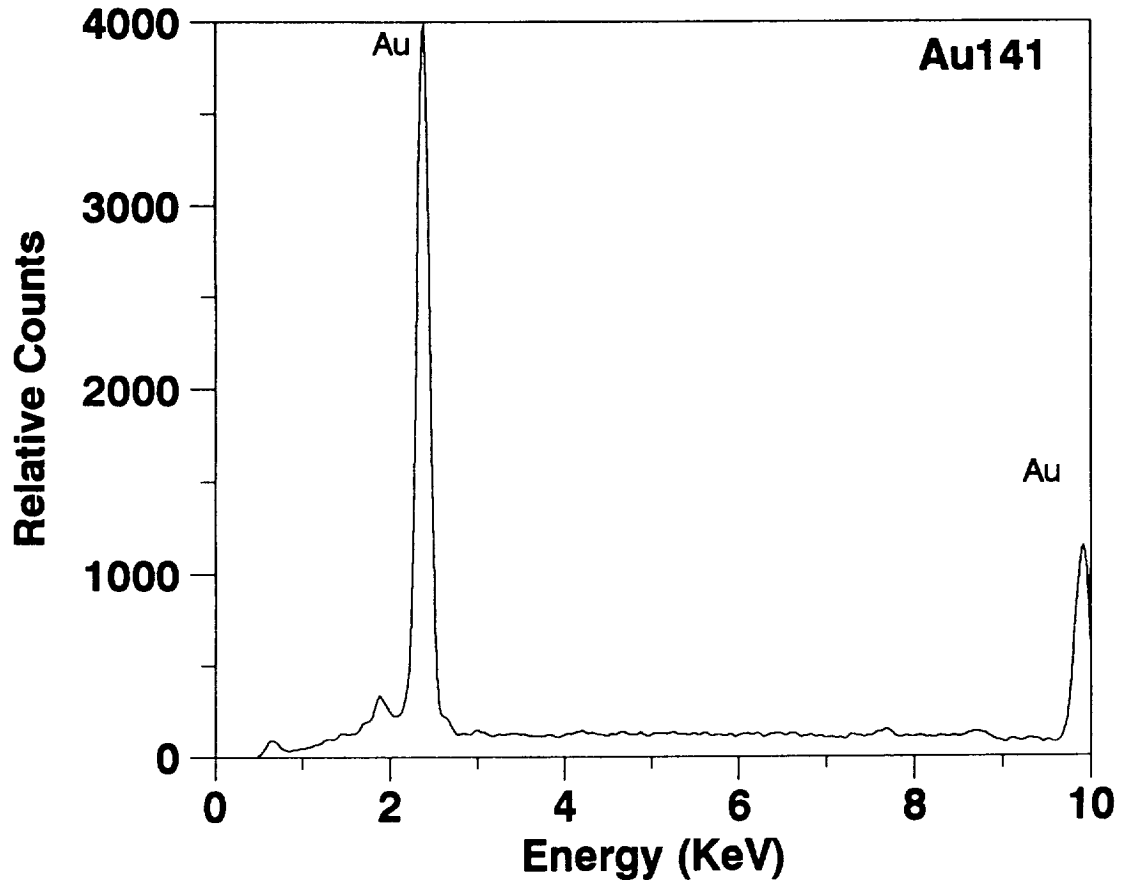
COMPONENT: E00F

FEATURE: 141

CORE: LD-68

DIAMETER: 40 μm

ORIGIN: Unknown



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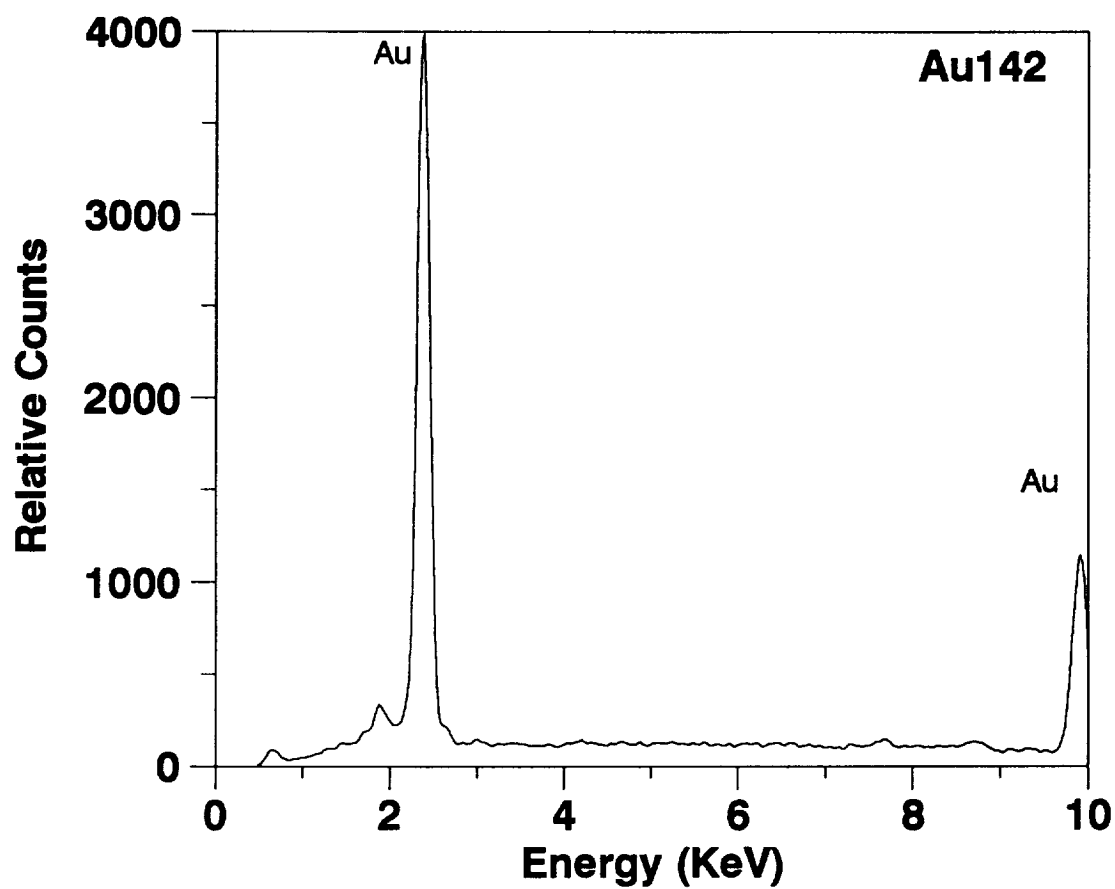
COMPONENT: E00F

FEATURE: 142

CORE: LD-69

DIAMETER: 20 μm

ORIGIN: Unknown

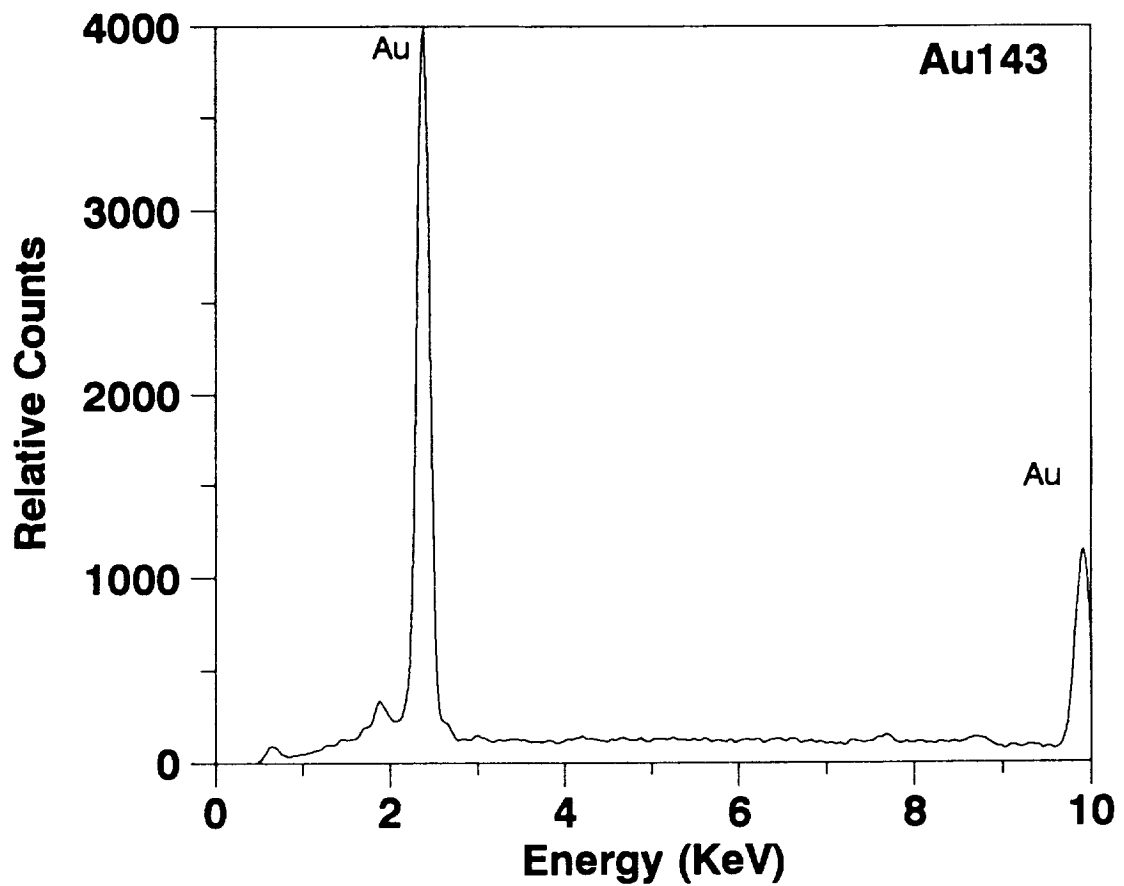


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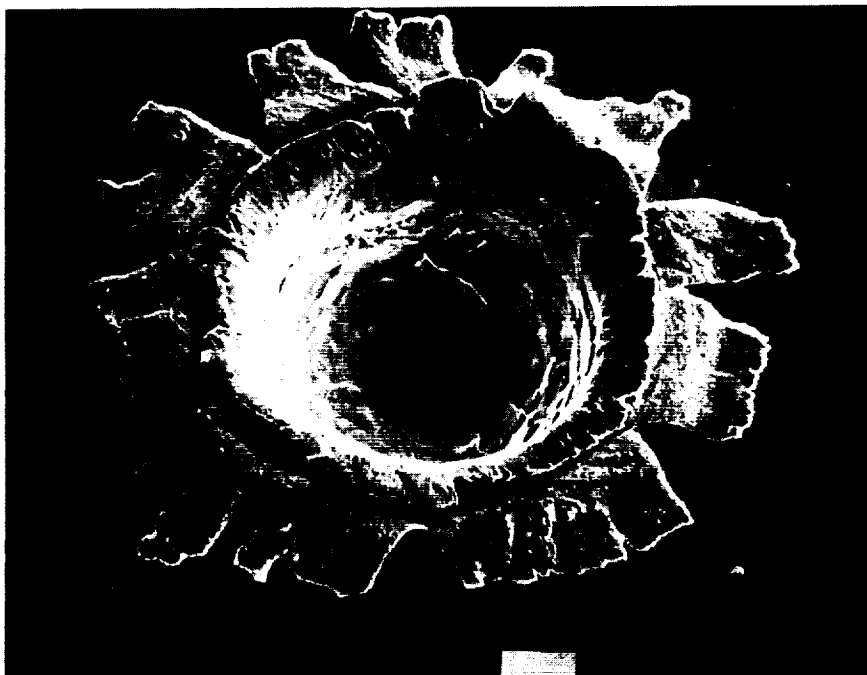


COMPONENT: E00F
FEATURE: 143
CORE: LD-67
DIAMETER: 65 μm
ORIGIN: Unknown

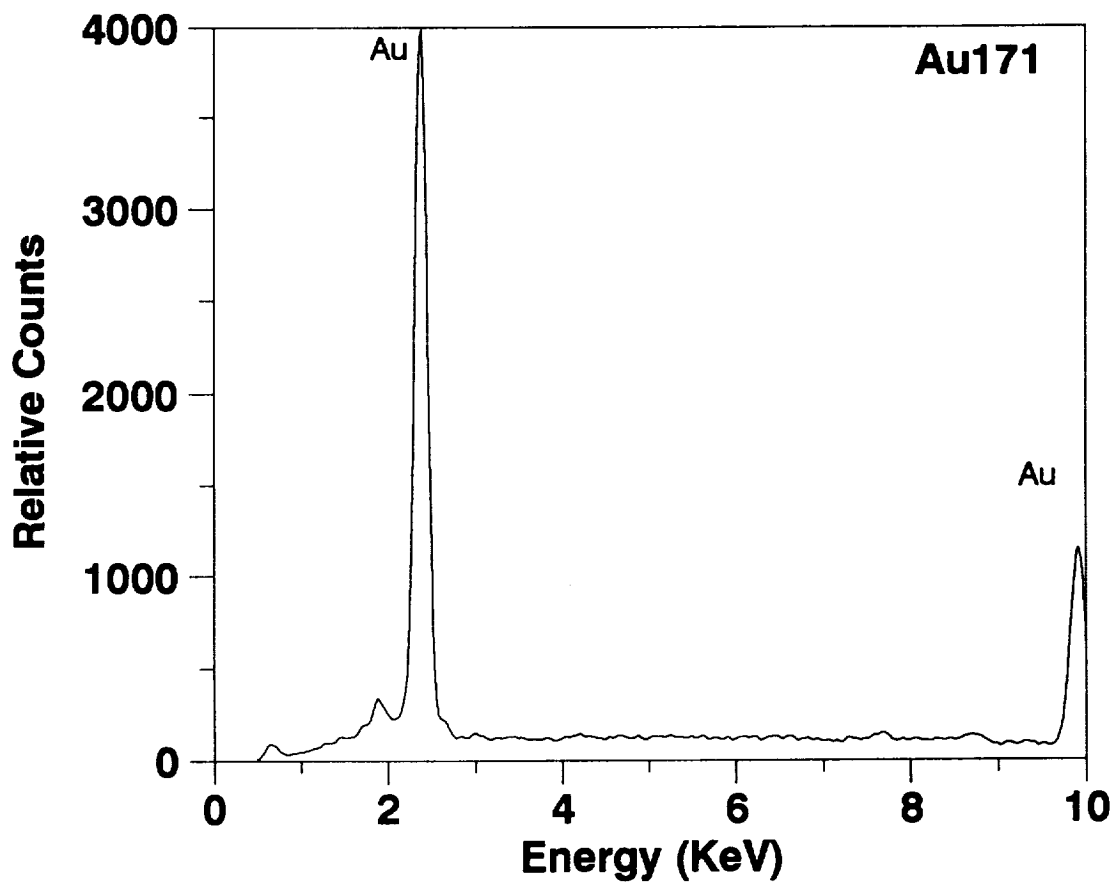


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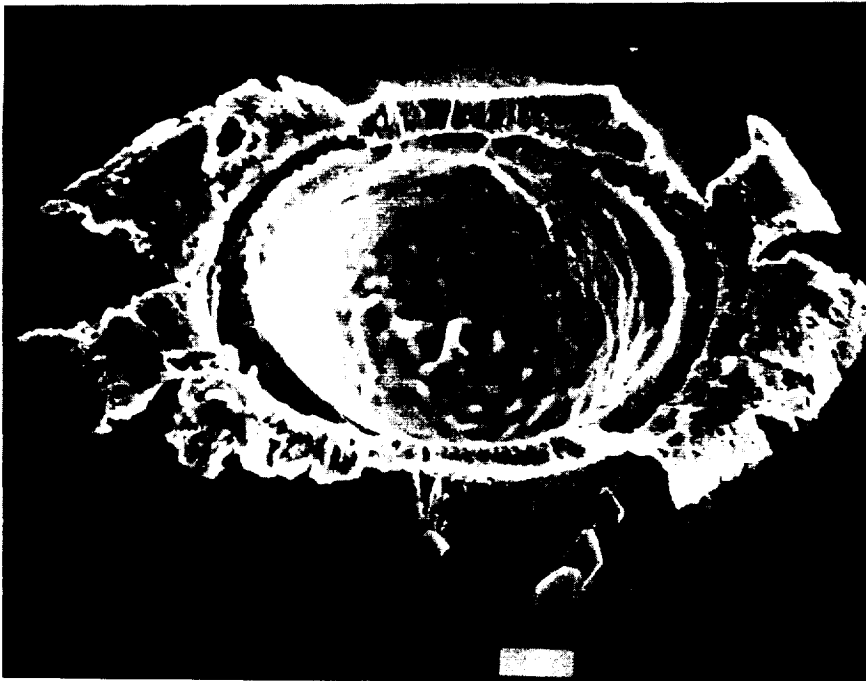


COMPONENT: EOOH
FEATURE: 171
CORE: LD-156
DIAMETER: 100 μm
ORIGIN: Unknown

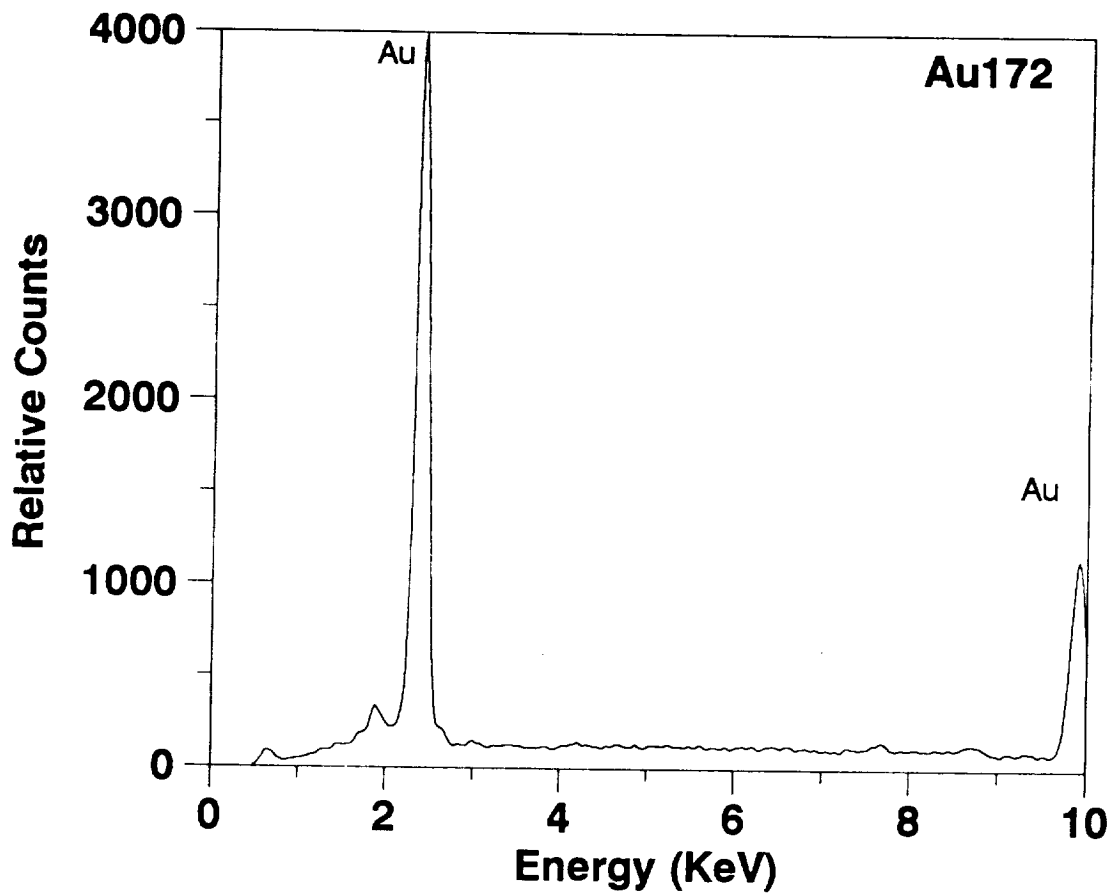


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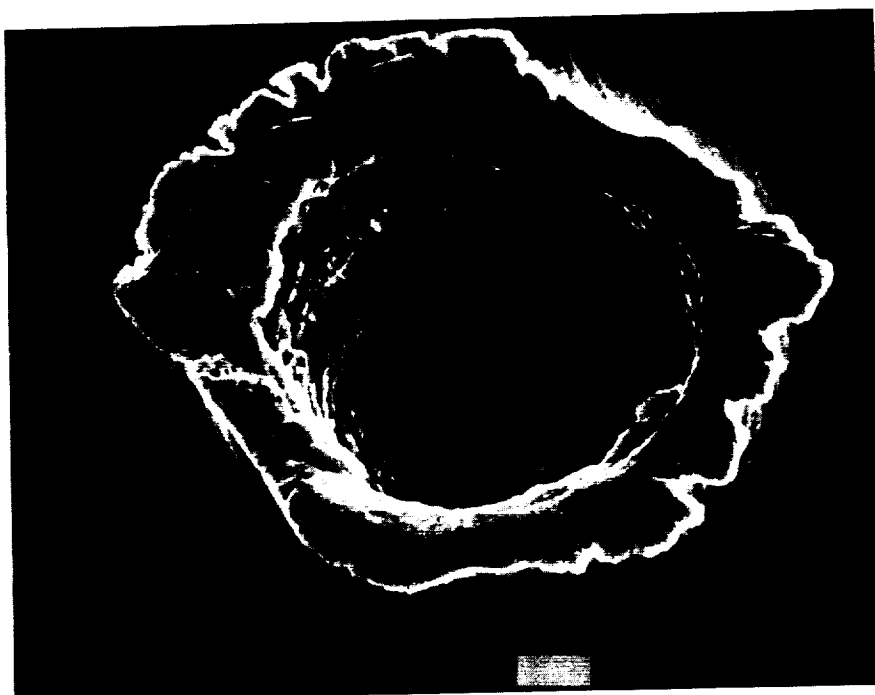


COMPONENT: EOOH
FEATURE: 172
CORE: LD-159
DIAMETER: 10 μm
ORIGIN: Unknown

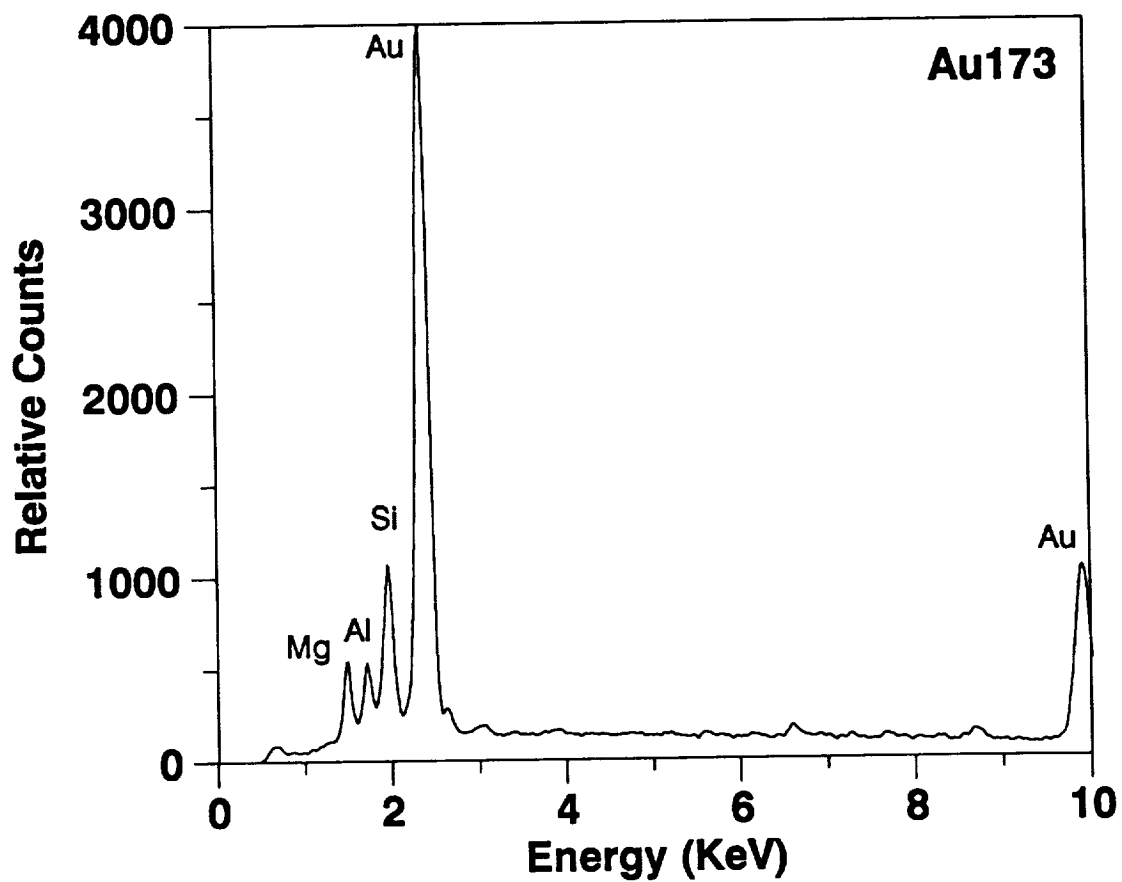


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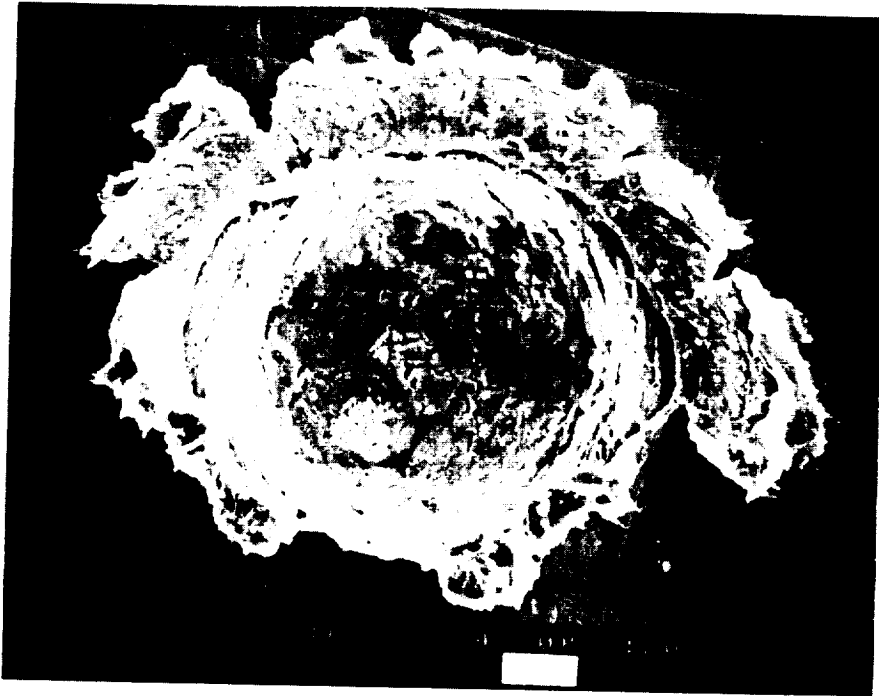


COMPONENT: EOOH
FEATURE: 173
CORE: LD-157
DIAMETER: 15 μ m
ORIGIN: Natural

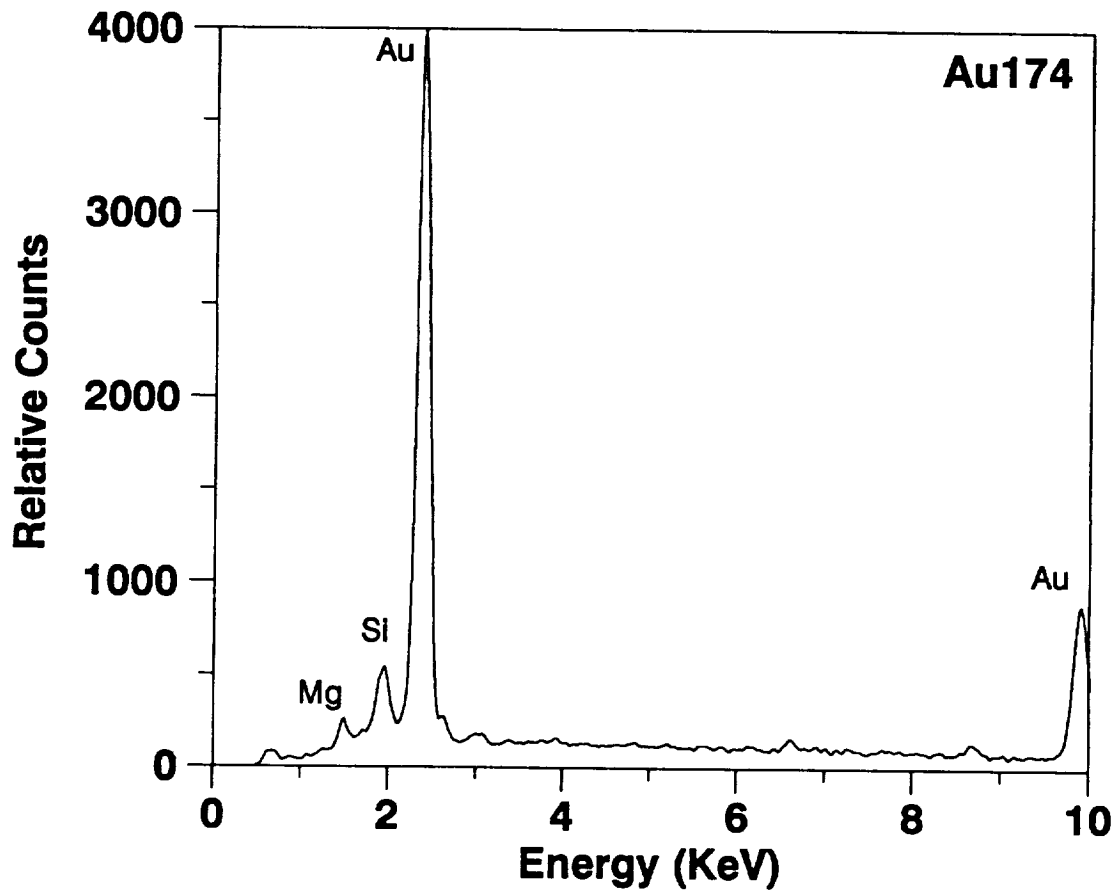


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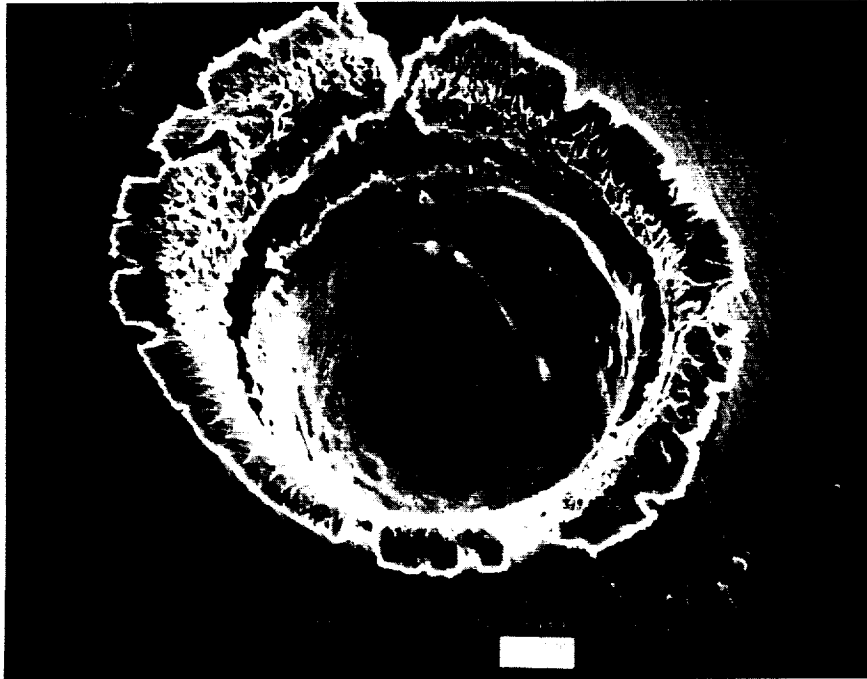


COMPONENT: EOOH
FEATURE: 174
CORE: LD-158
DIAMETER: 30 μ m
ORIGIN: Natural



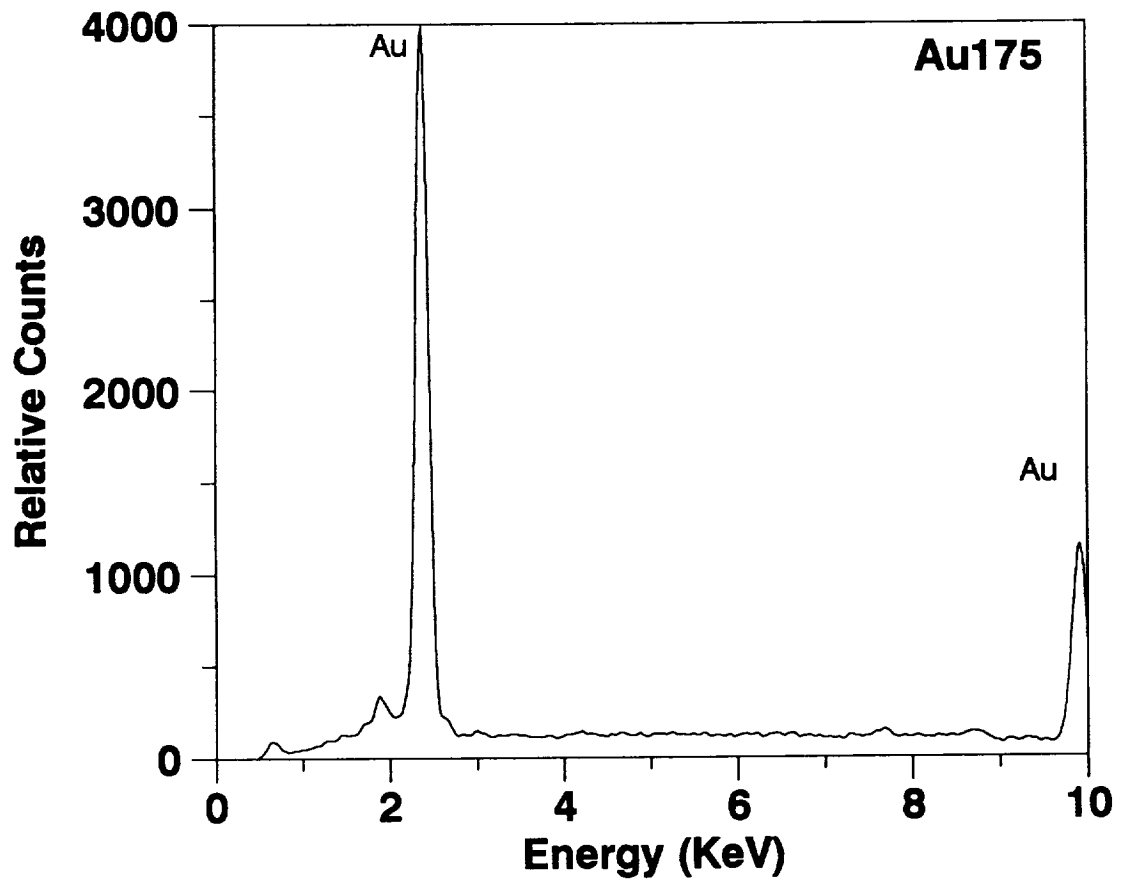
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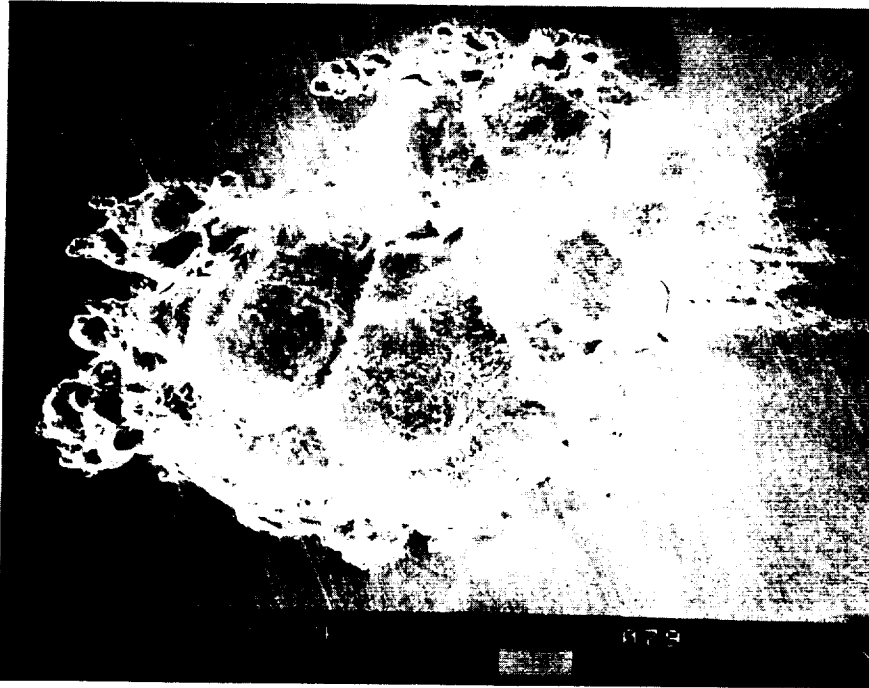
COMPONENT: EOOH
FEATURE: 175
CORE: LD-125

DIAMETER: 25 μm
ORIGIN: Unknown

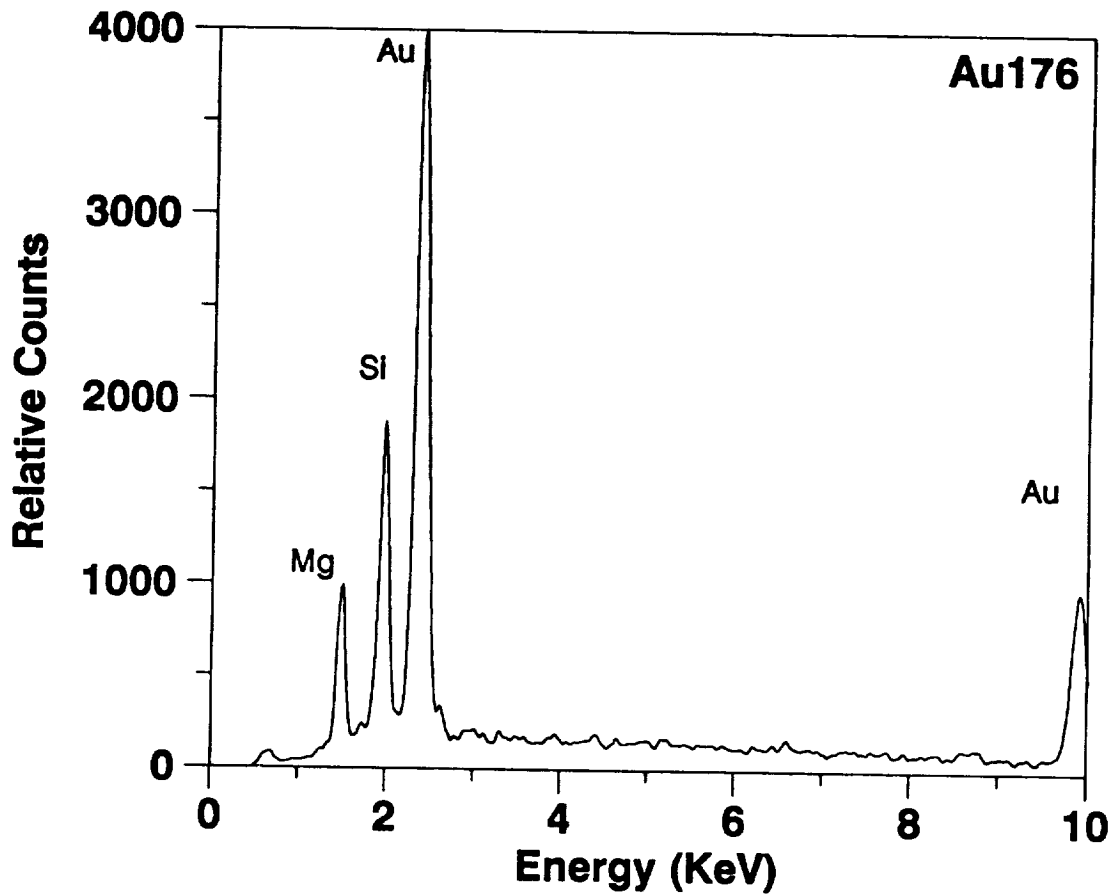


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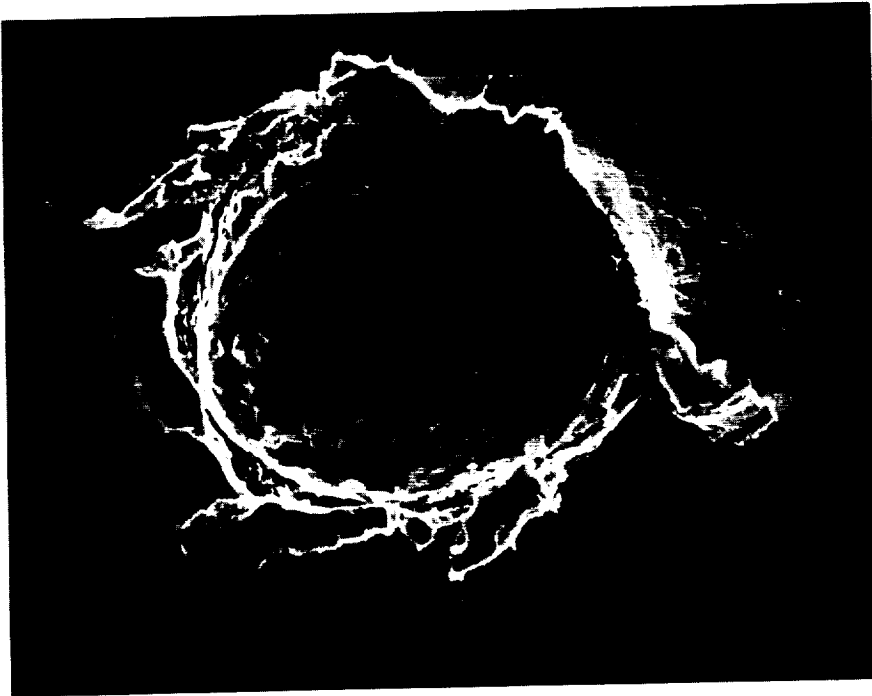


COMPONENT: EOOH
FEATURE: 176
CORE: LD-124
DIAMETER: 245 μm
ORIGIN: Natural

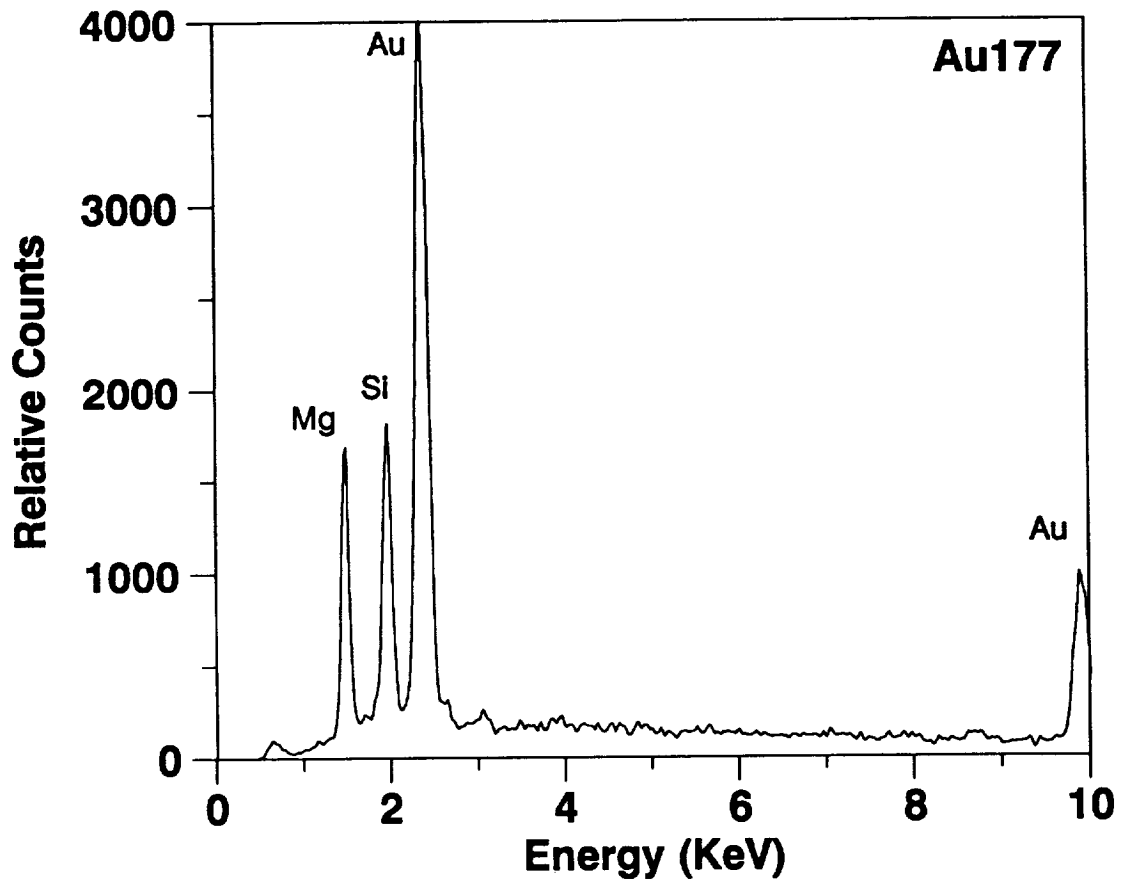


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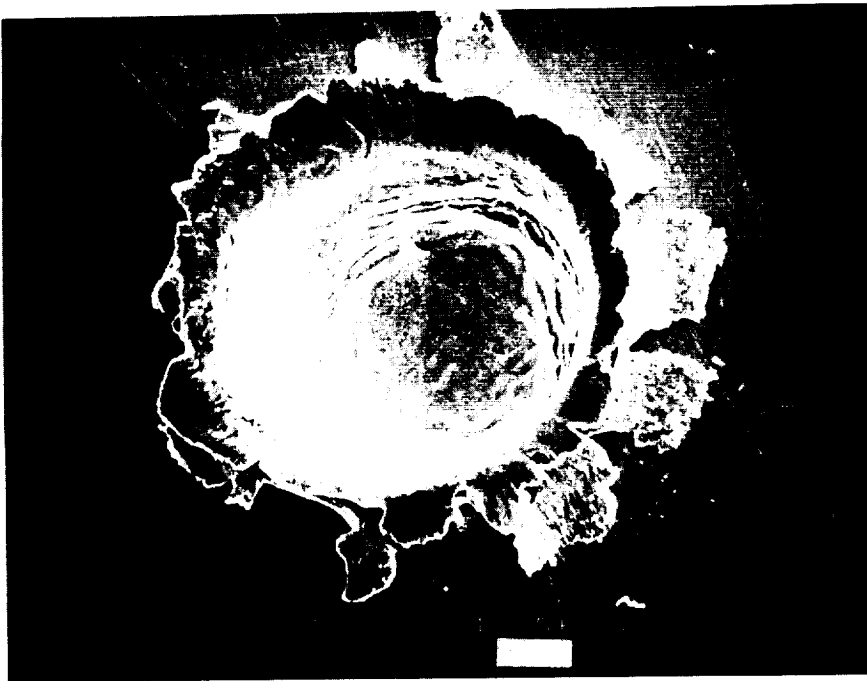


COMPONENT: EOOH
FEATURE: 177
CORE: LD-121
DIAMETER: 30 μm
ORIGIN: Natural



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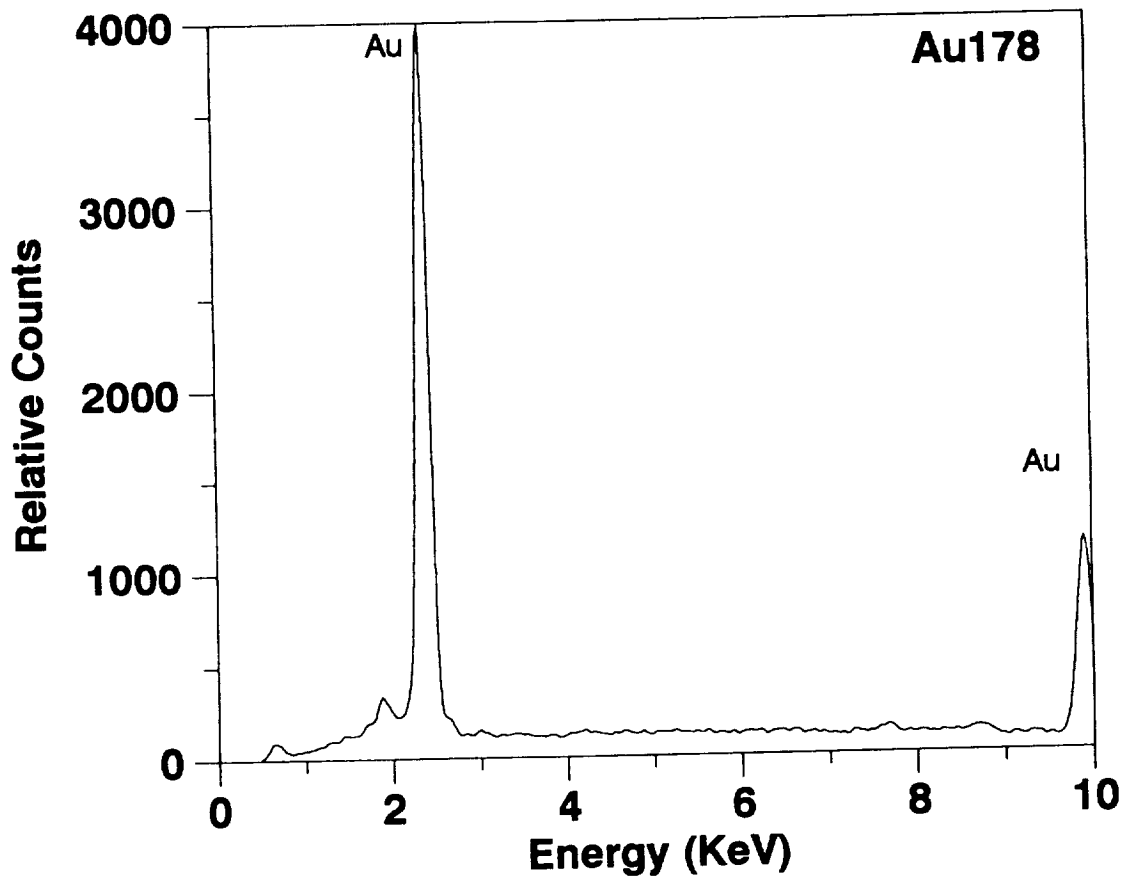
COMPONENT: EOOH

FEATURE: 178

CORE: LD-126

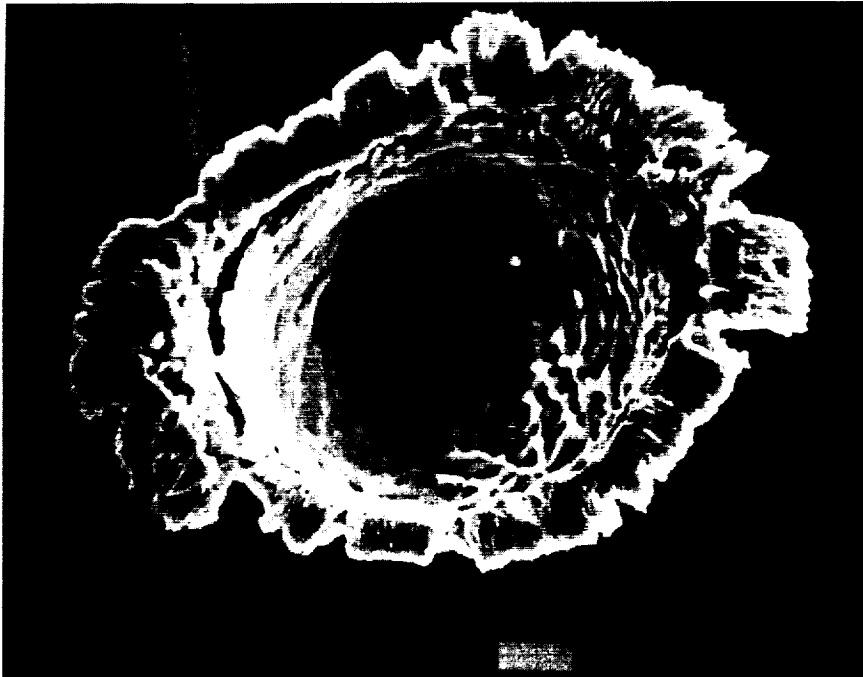
DIAMETER: 55 μm

ORIGIN: Unknown

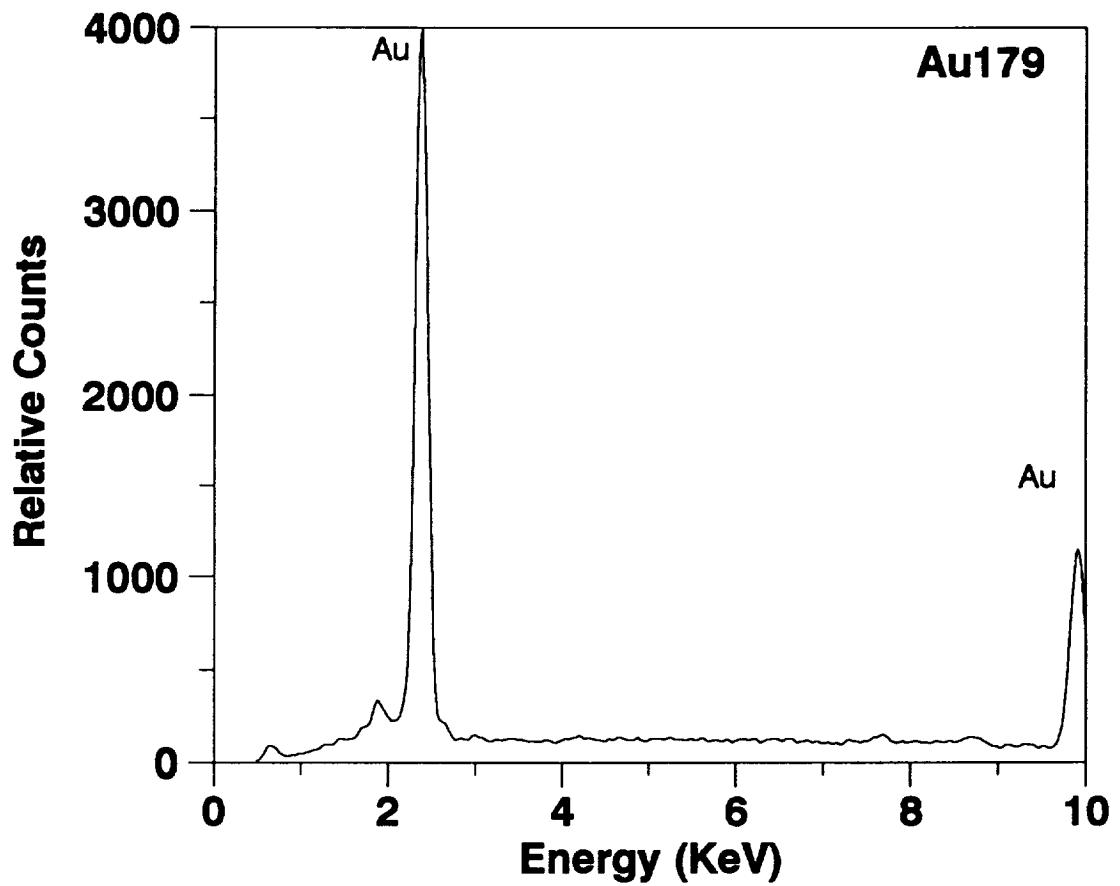


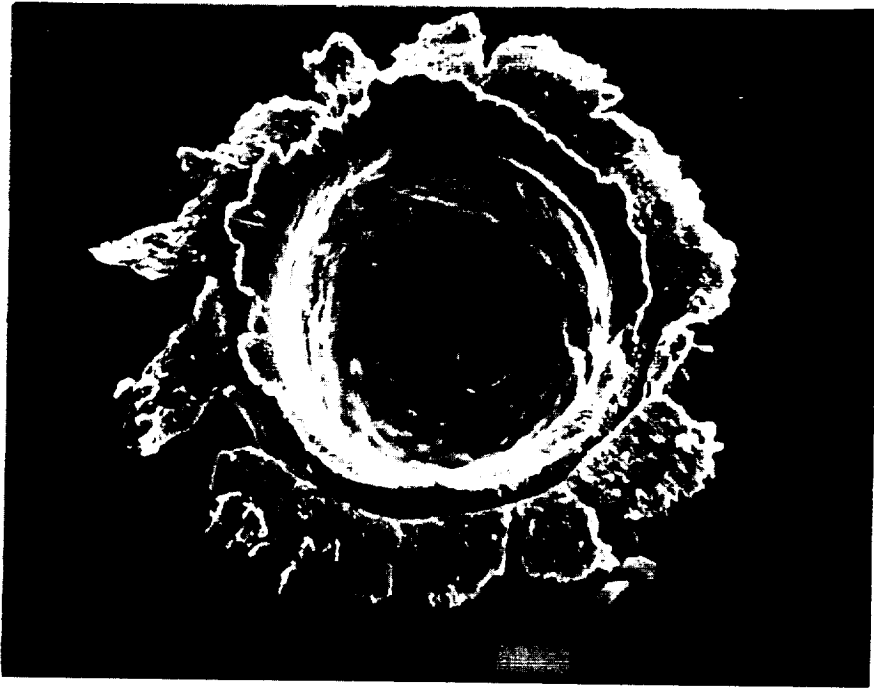
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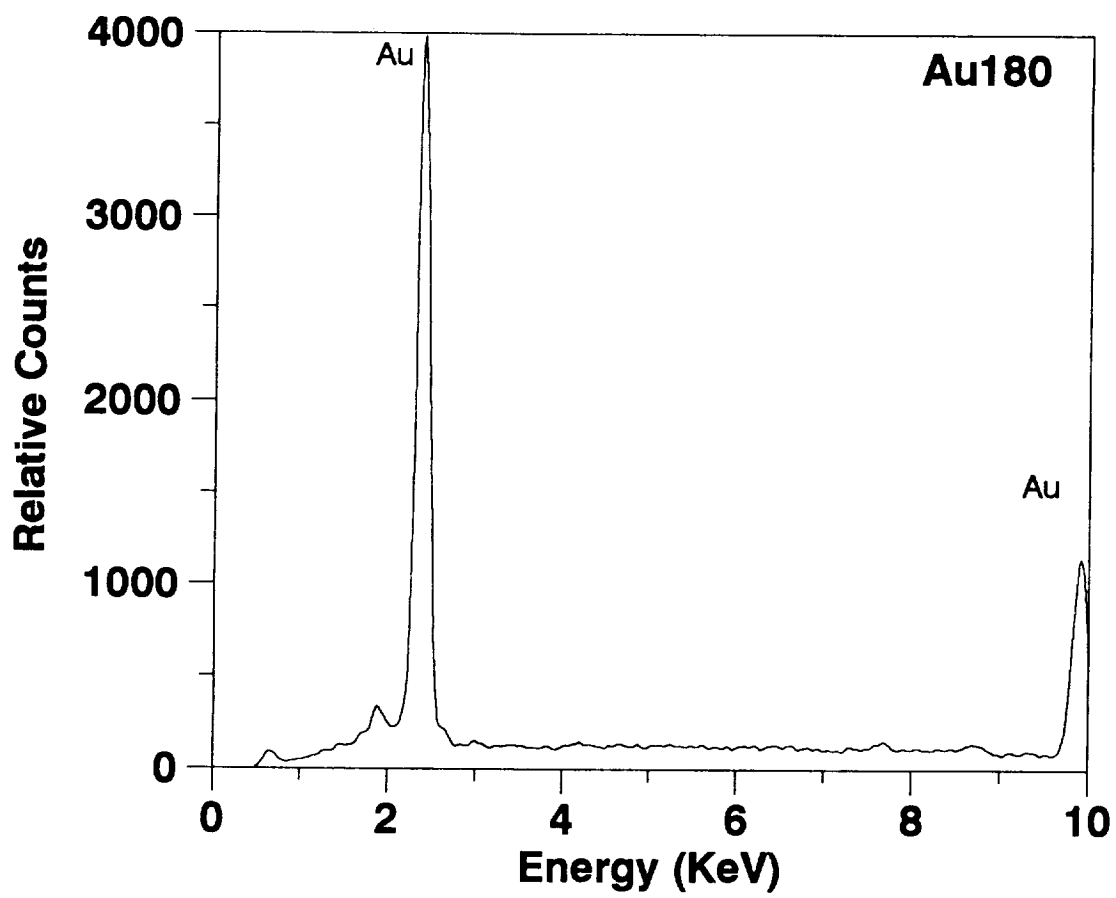


COMPONENT: EOOH
FEATURE: 179
CORE: LD-122
DIAMETER: 15 μm
ORIGIN: Unknown



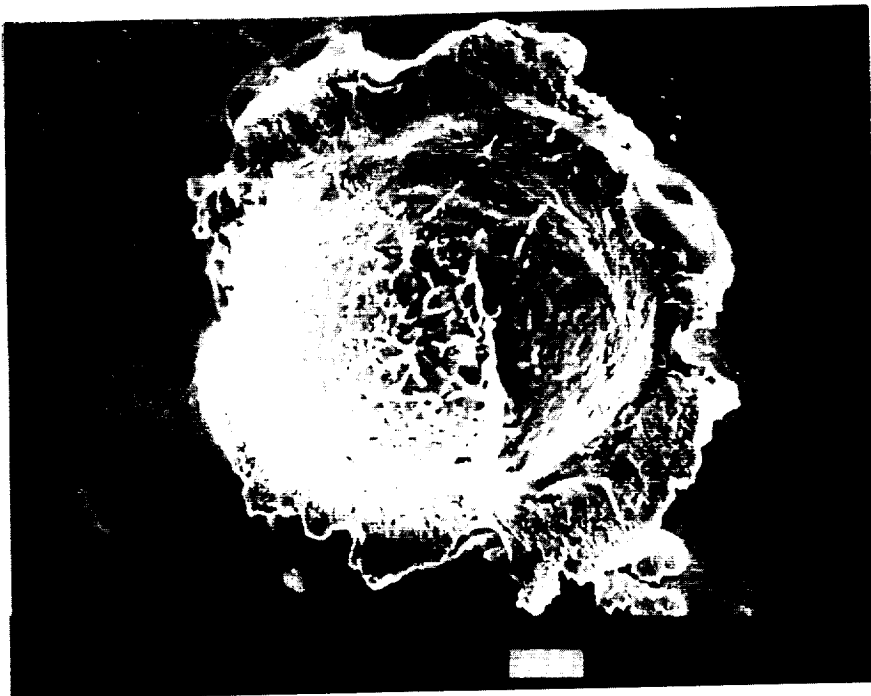


COMPONENT: EOOH
FEATURE: 180
CORE: LD-127
DIAMETER: 35 μm
ORIGIN: Unknown

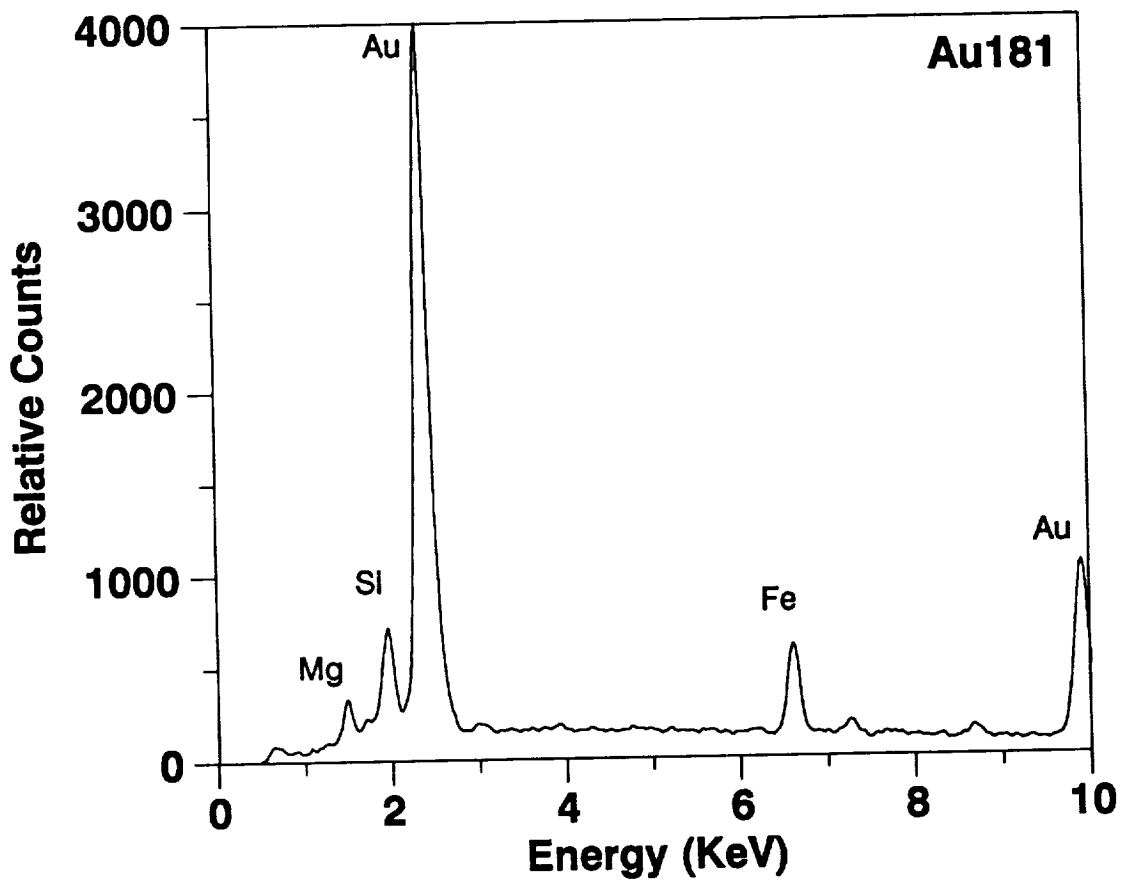


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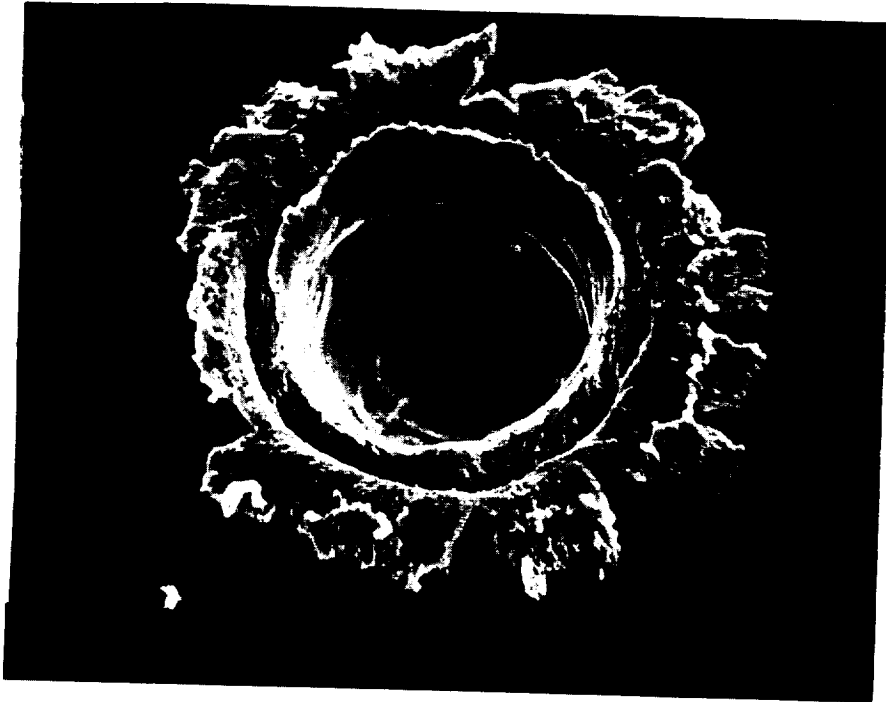


COMPONENT: EOOH
FEATURE: 181
CORE: LD-123
DIAMETER: 65 μm
ORIGIN: Natural

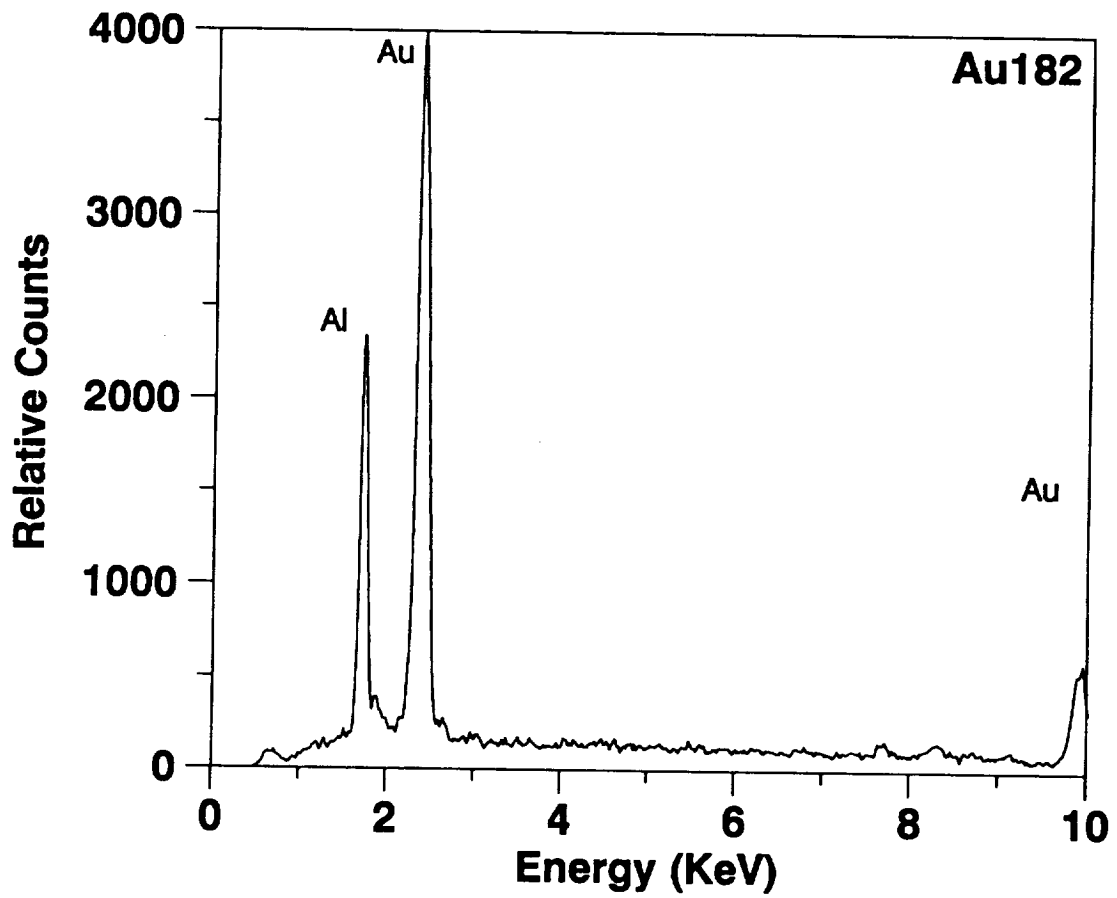


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COMPONENT: EOOH
FEATURE: 182
CORE: LD-128
DIAMETER: 20 μm
ORIGIN: Man-made

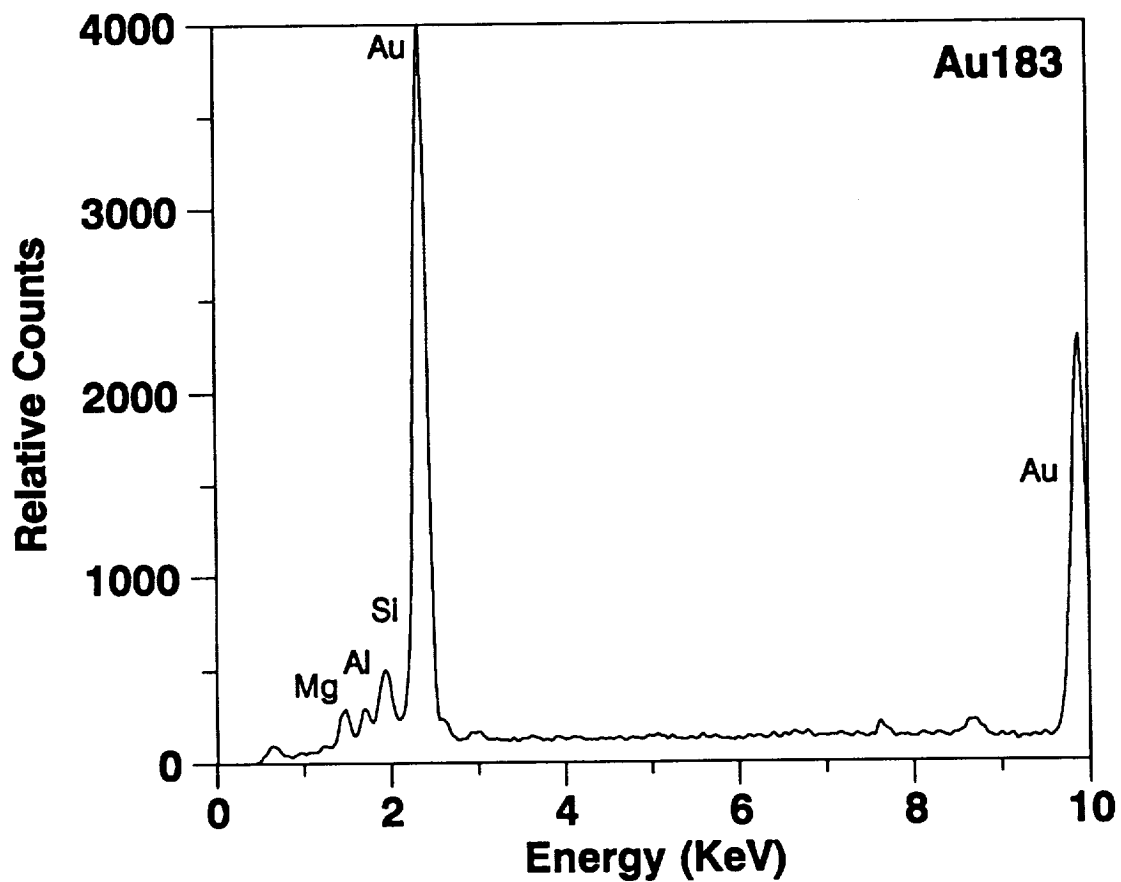


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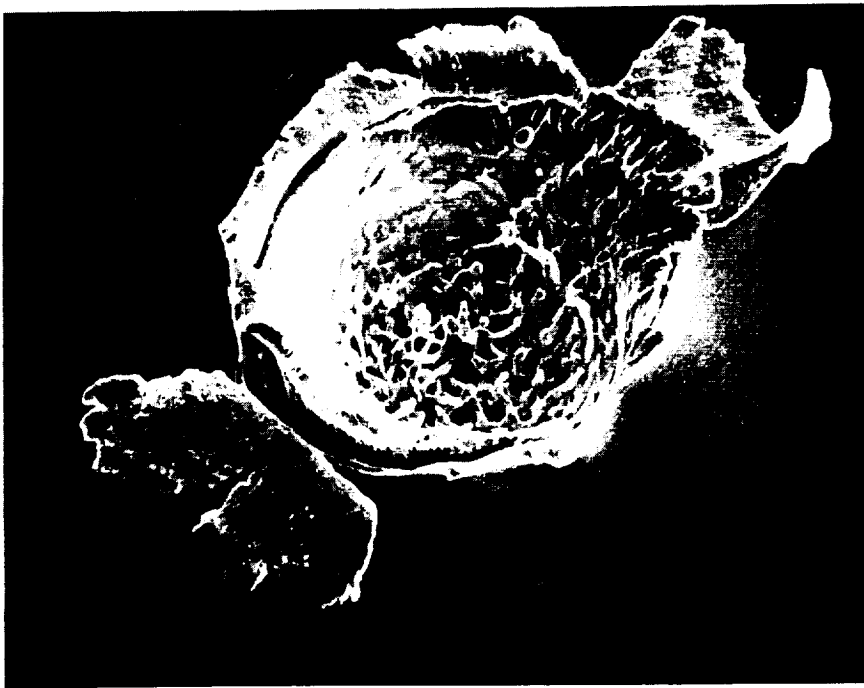


COMPONENT: EOOH
FEATURE: 183
CORE: LD-129
DIAMETER: 35 μm
ORIGIN: Natural



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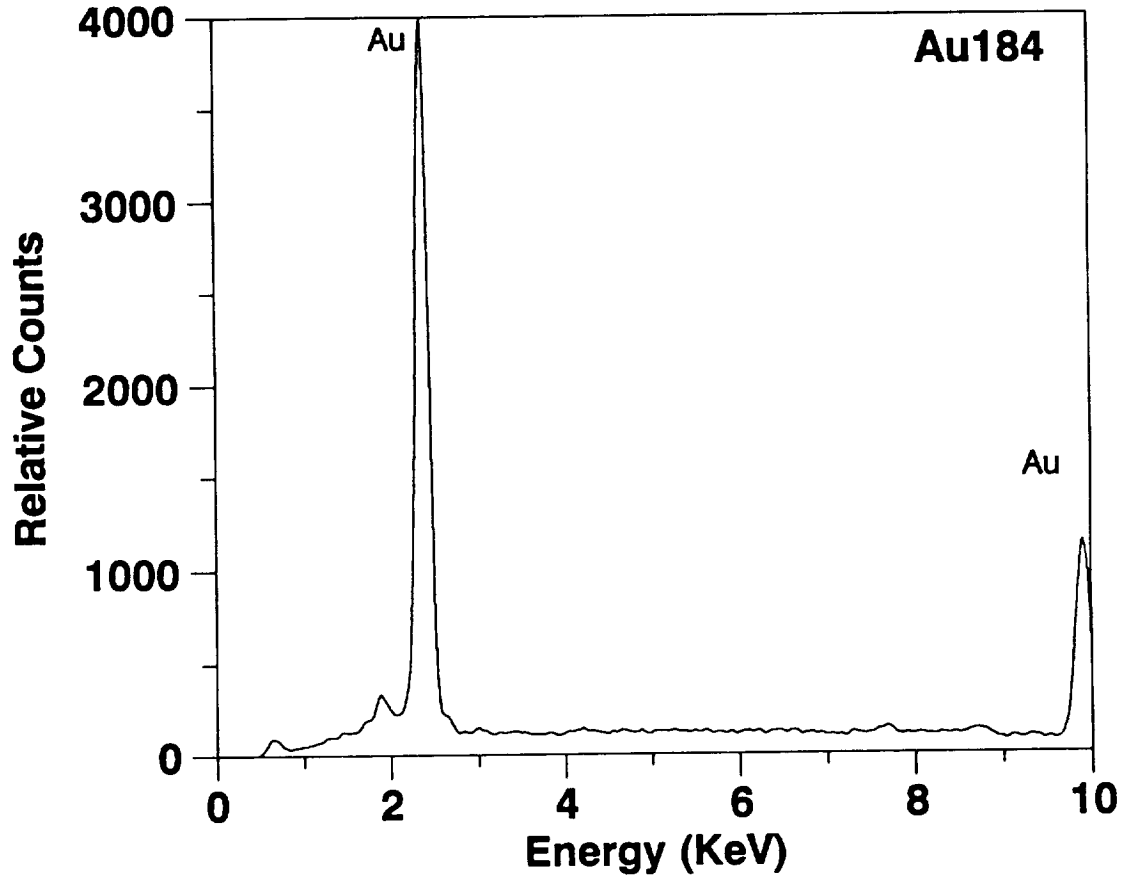
COMPONENT: EOOH

FEATURE: 184

CORE: LD-129

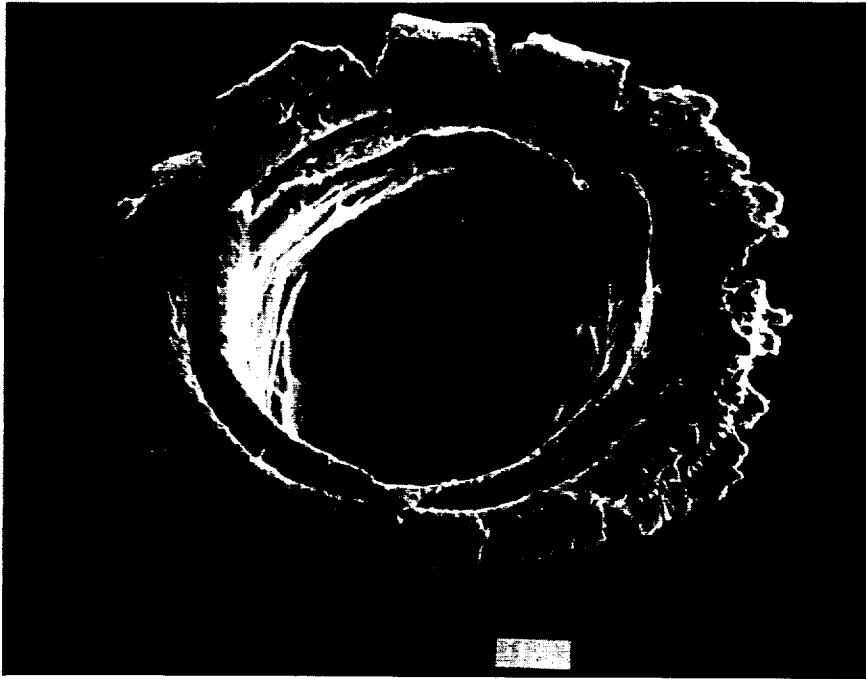
DIAMETER: 60 μm

ORIGIN: Unknown

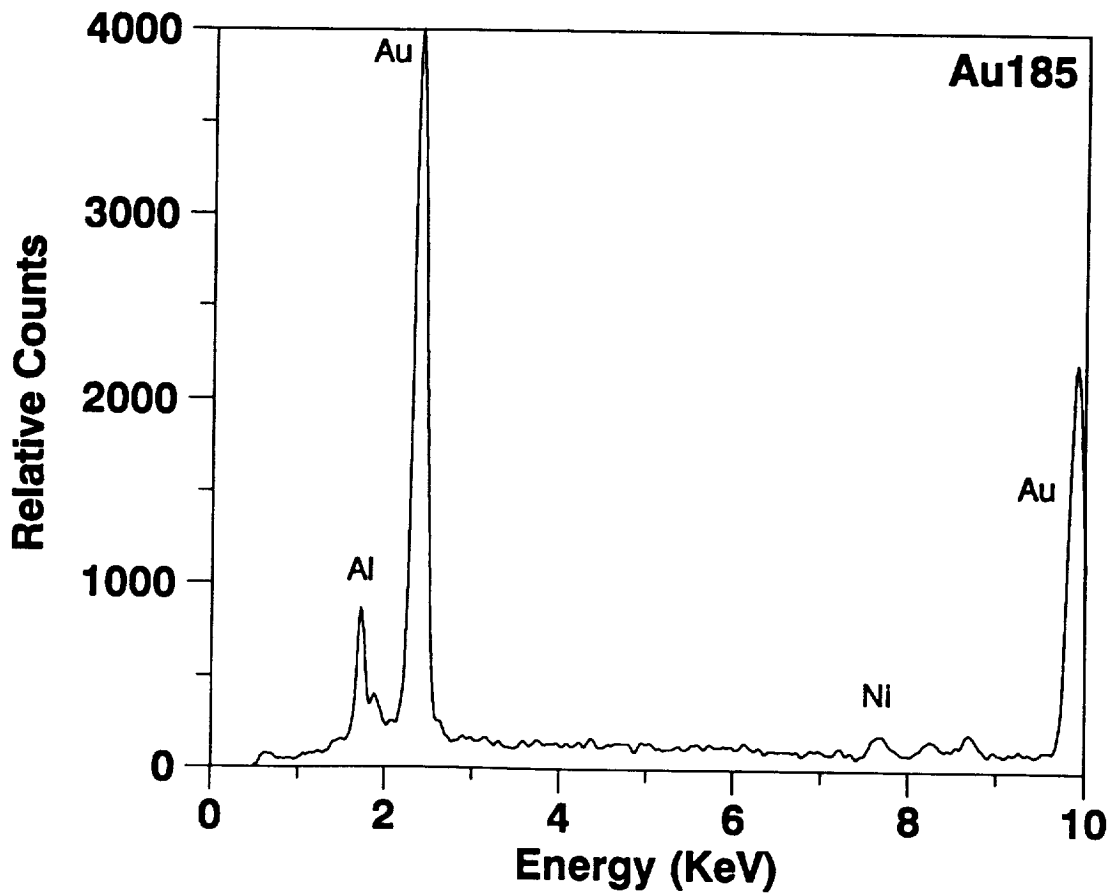


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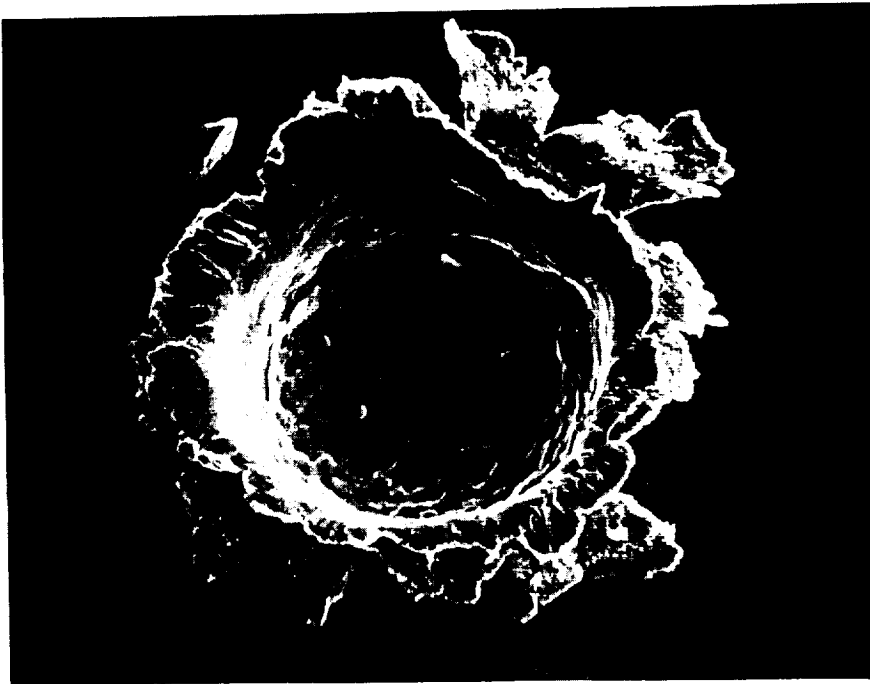


COMPONENT: EOOH
FEATURE: 185
CORE: LD-130
DIAMETER: 45 μ m
ORIGIN: Man-made

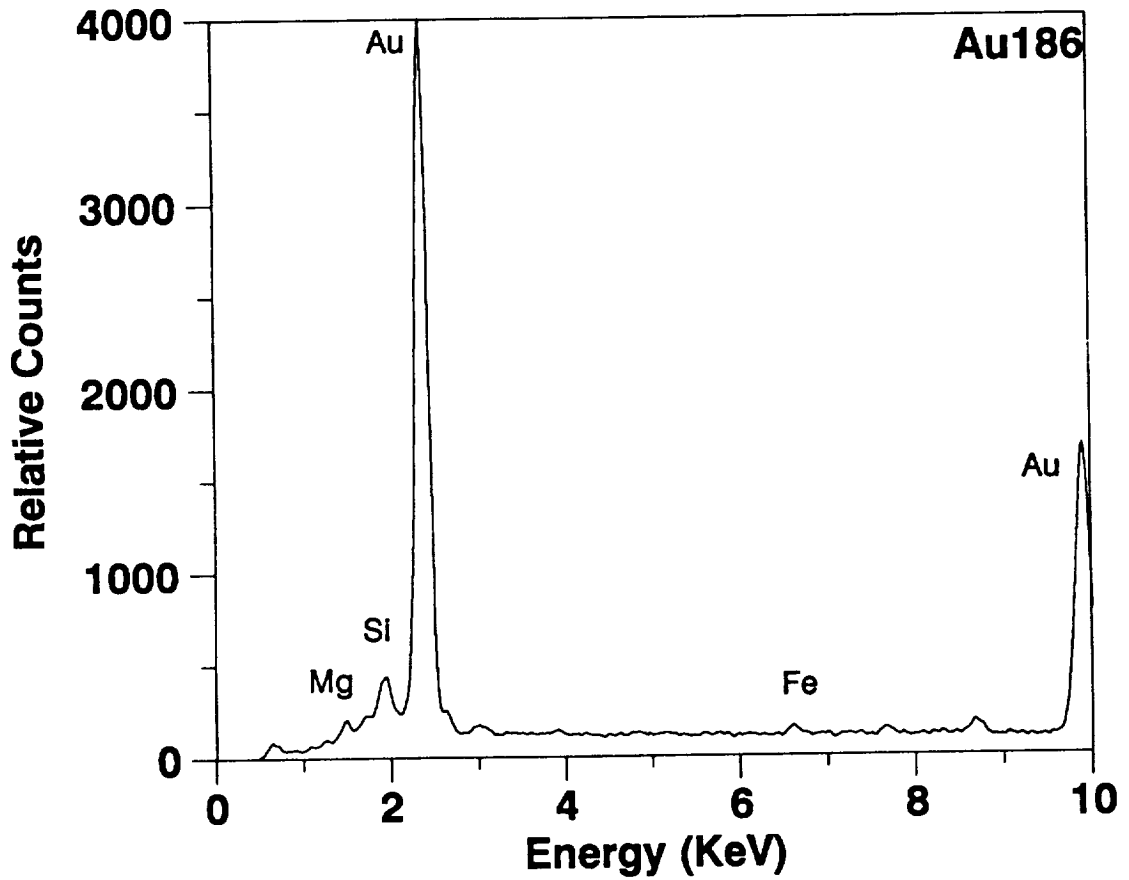


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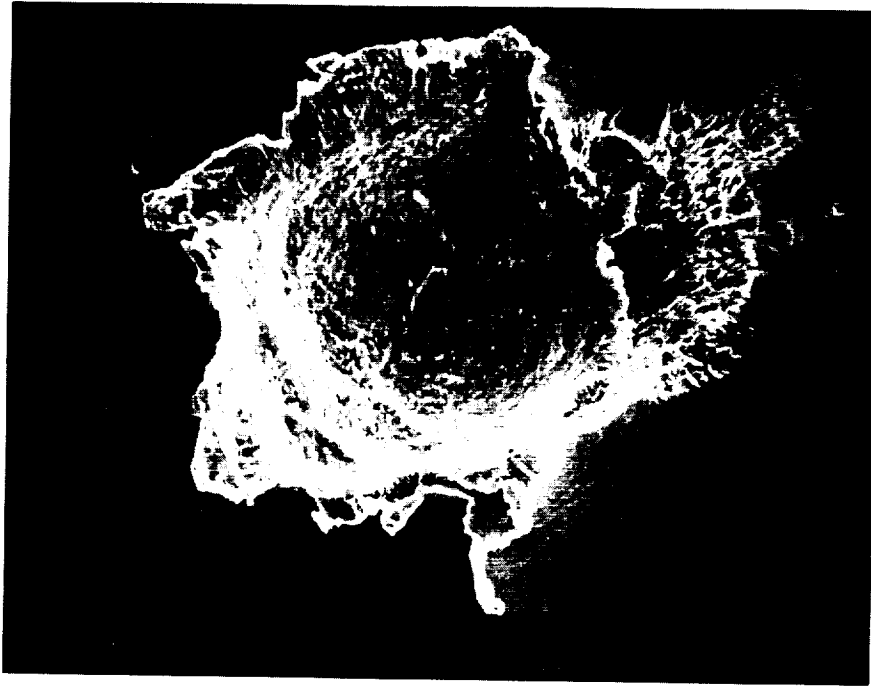
COMPONENT: EOOH
FEATURE: 186
CORE: LD-131
DIAMETER: 40 μ m
ORIGIN: Natural



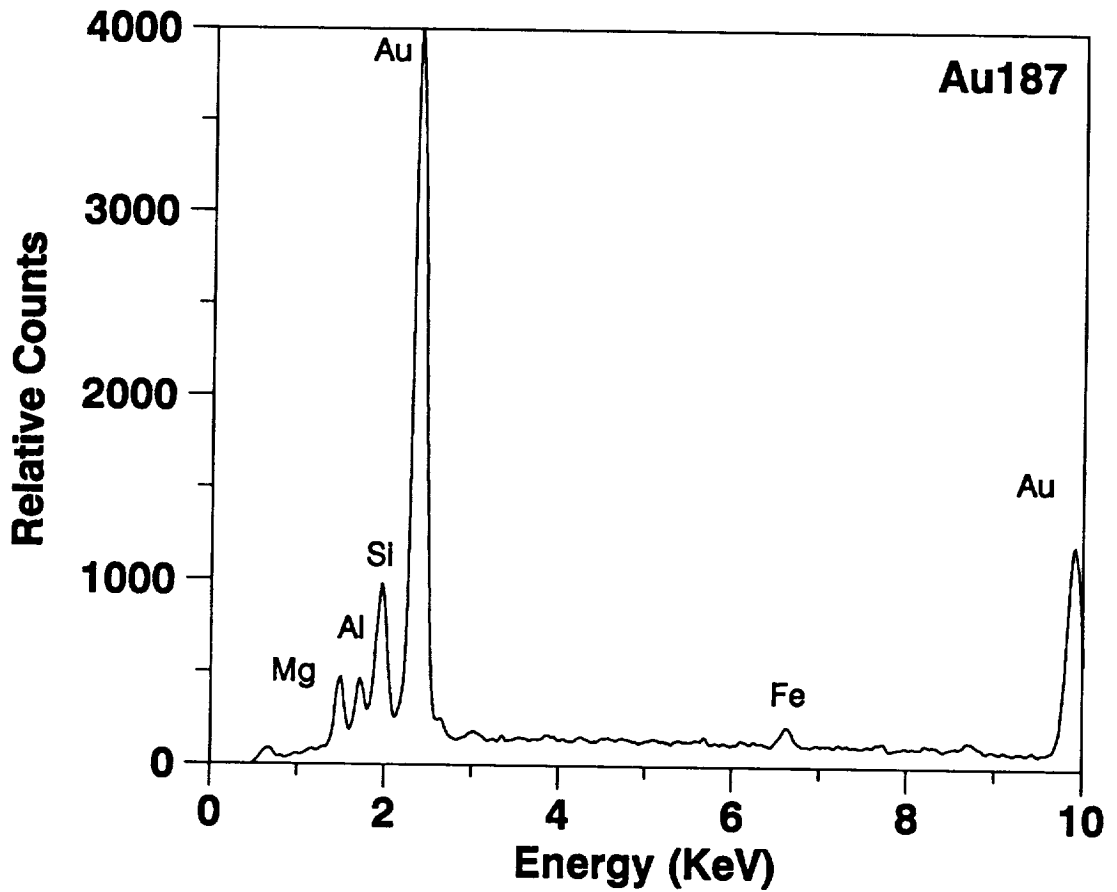
C-2

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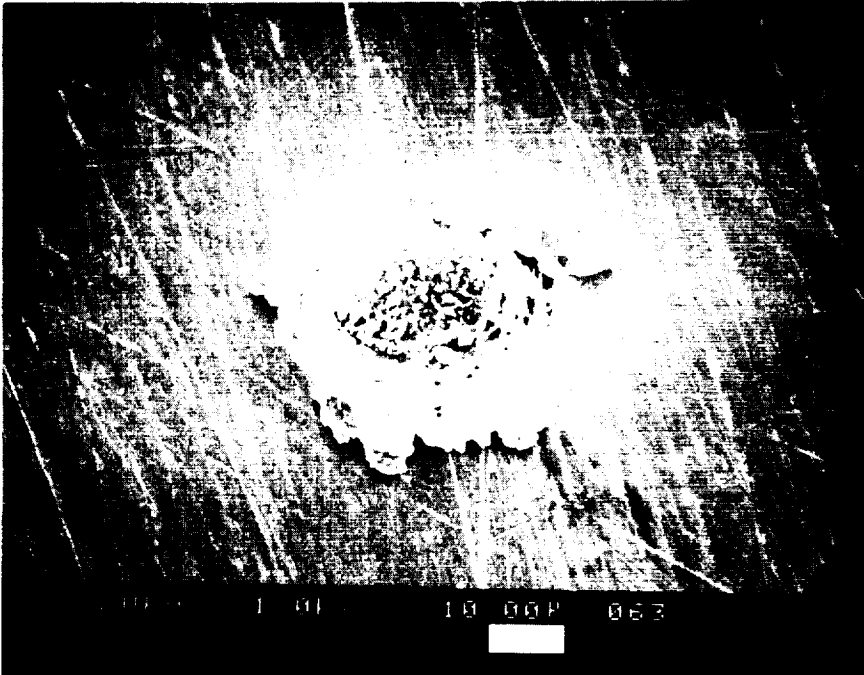


COMPONENT: EOOH
FEATURE: 187
CORE: LD-132
DIAMETER: 60 μ m
ORIGIN: Natural

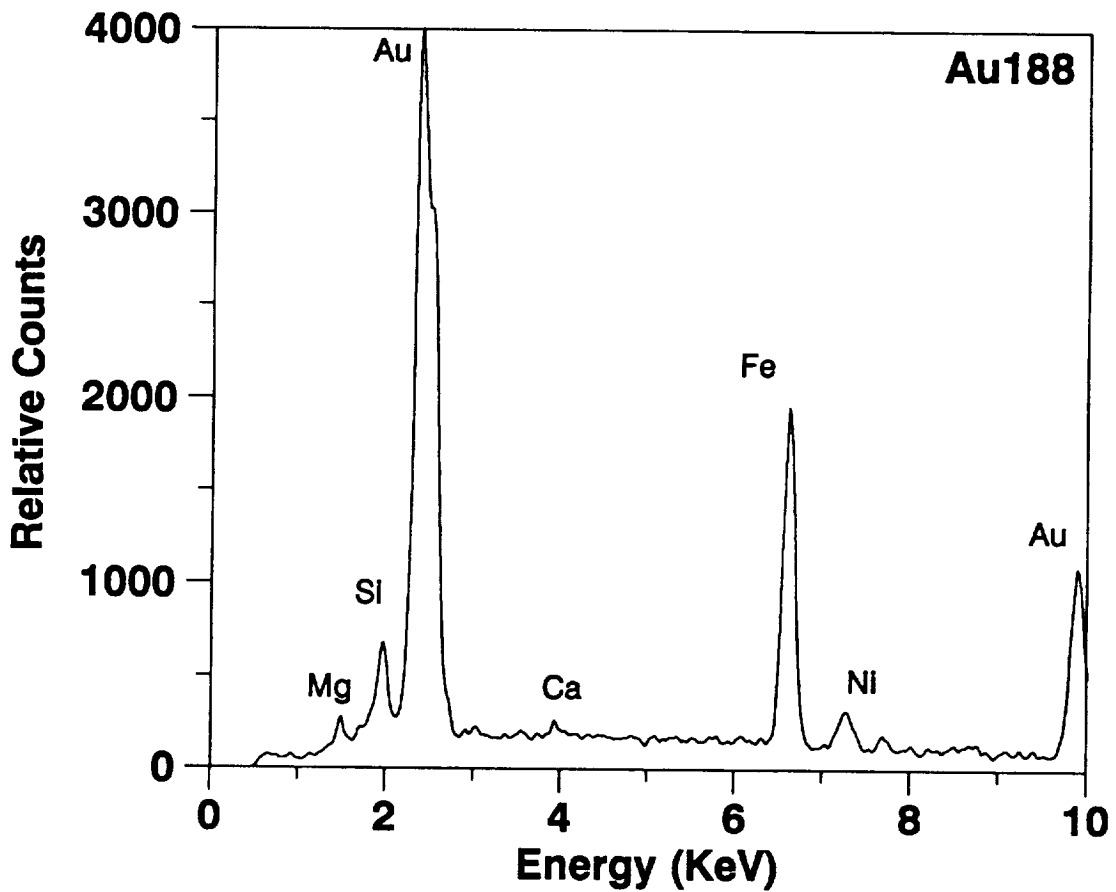


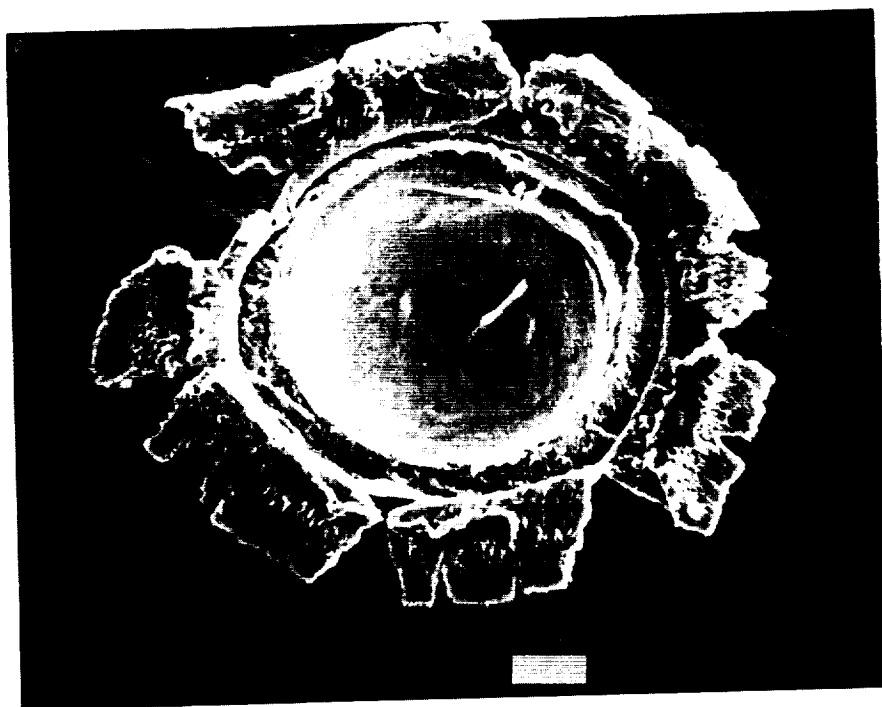
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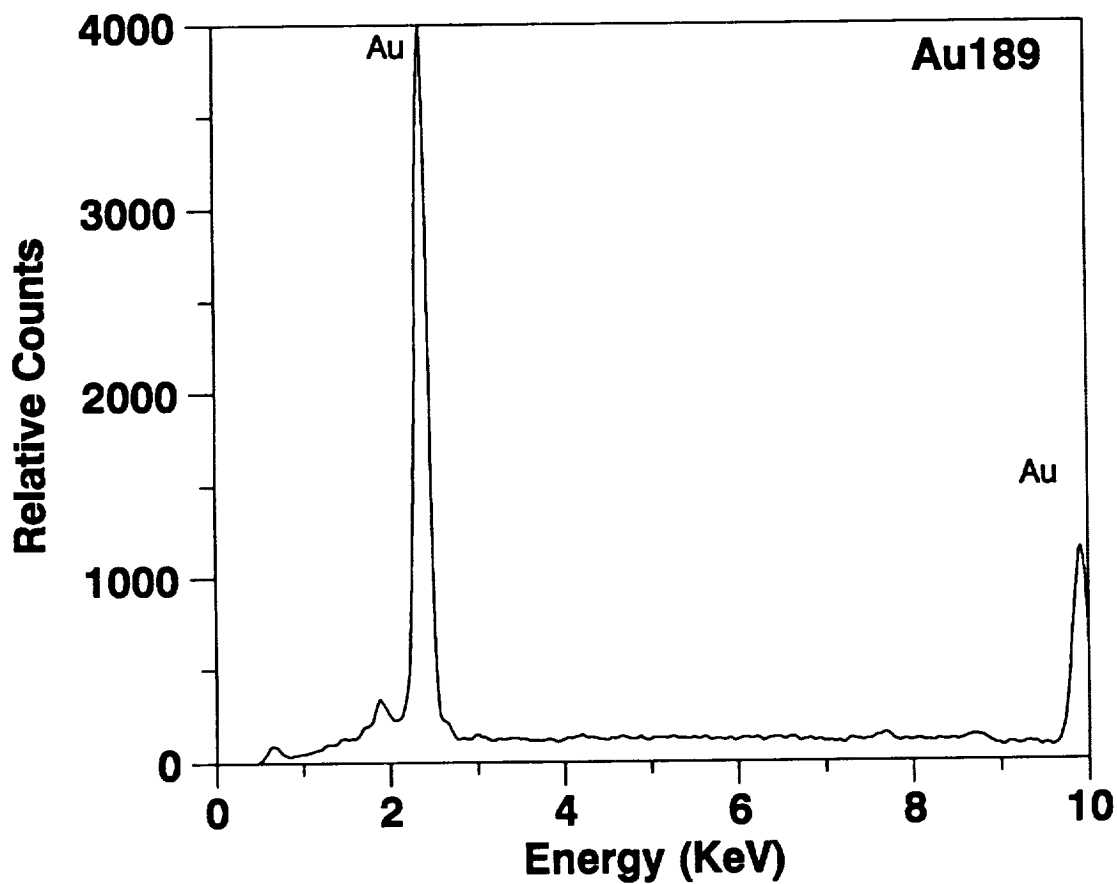


COMPONENT: EOOH
FEATURE: 188
CORE: LD-133
DIAMETER: 25 μm
ORIGIN: Natural



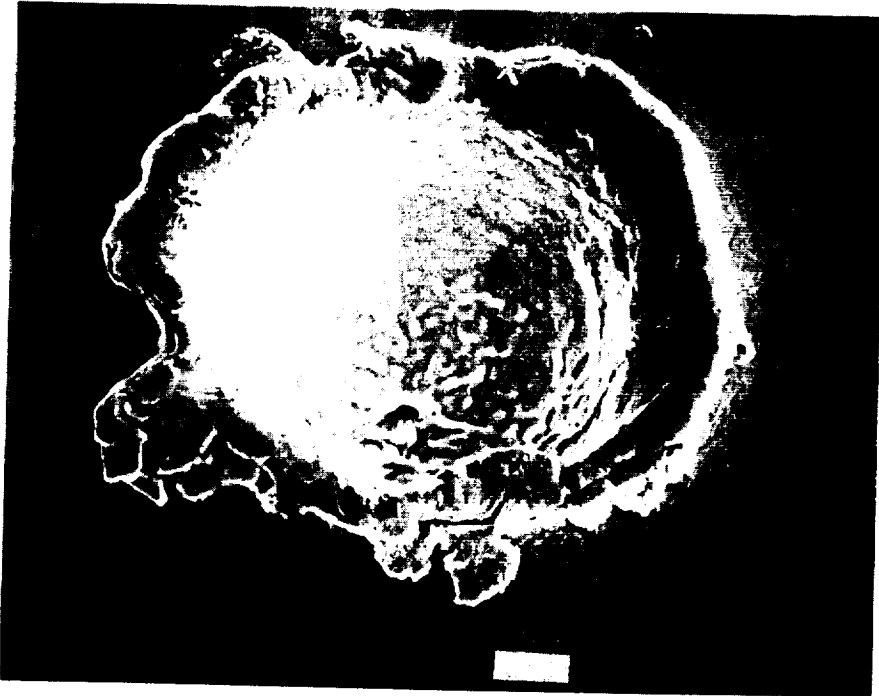


COMPONENT: EOOH
FEATURE: 189
CORE: LD-136
DIAMETER: 25 μ m
ORIGIN: Unknown

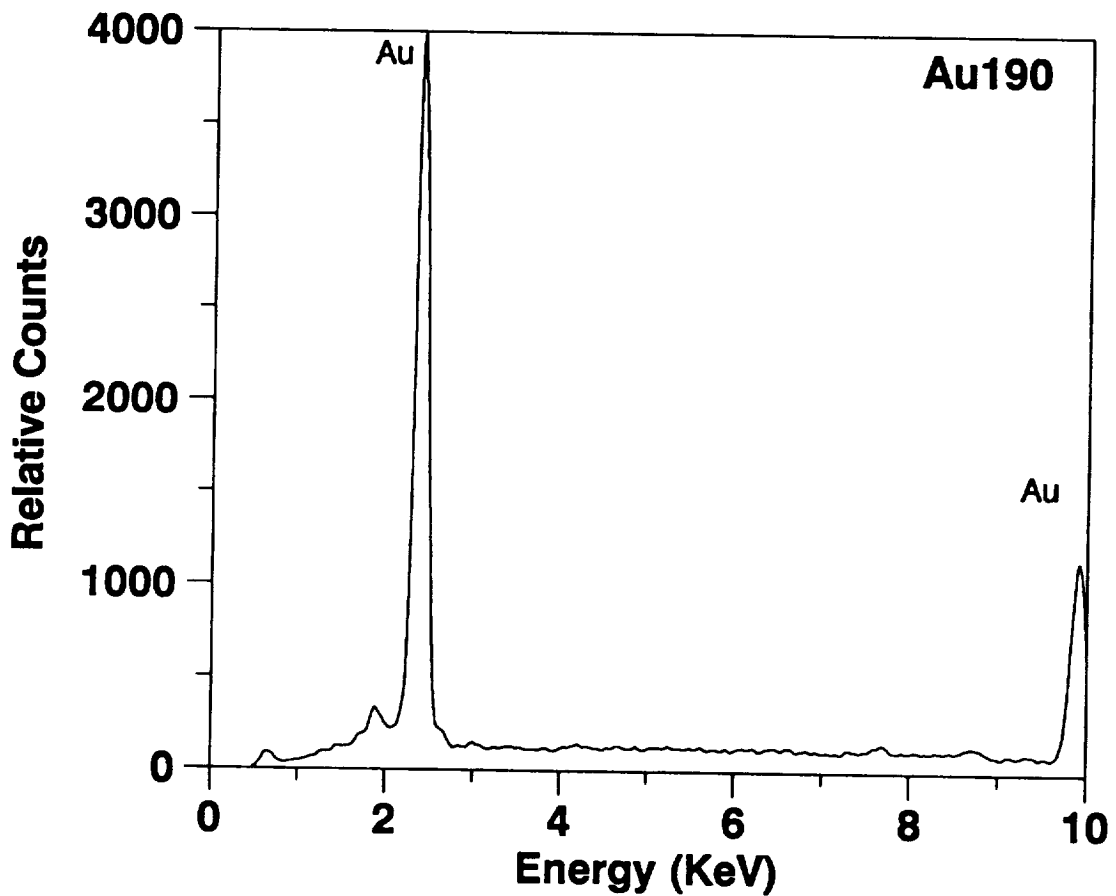


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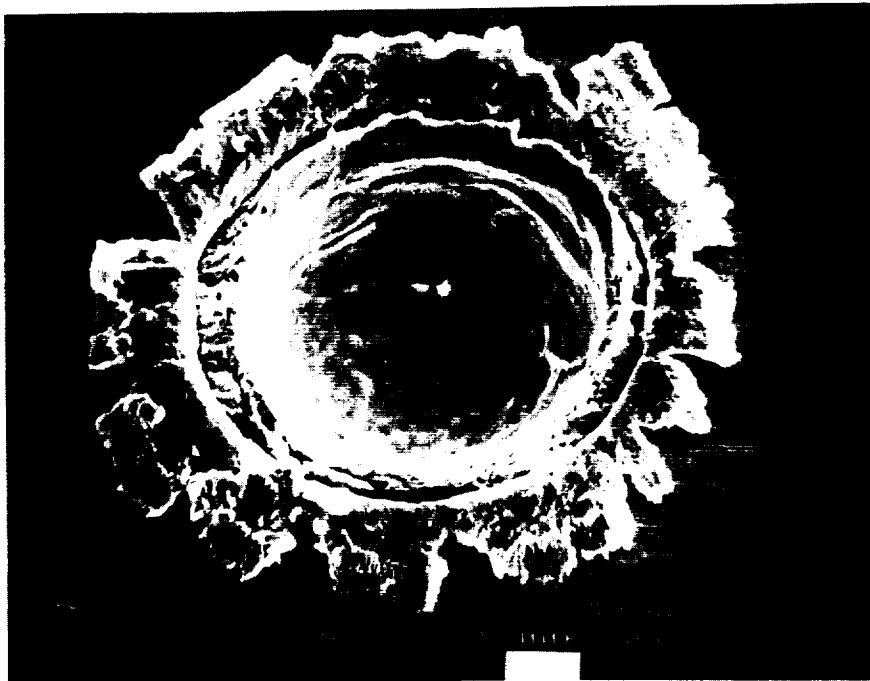


COMPONENT: EOOH
FEATURE: 190
CORE: LD-134
DIAMETER: 40 μ m
ORIGIN: Unknown

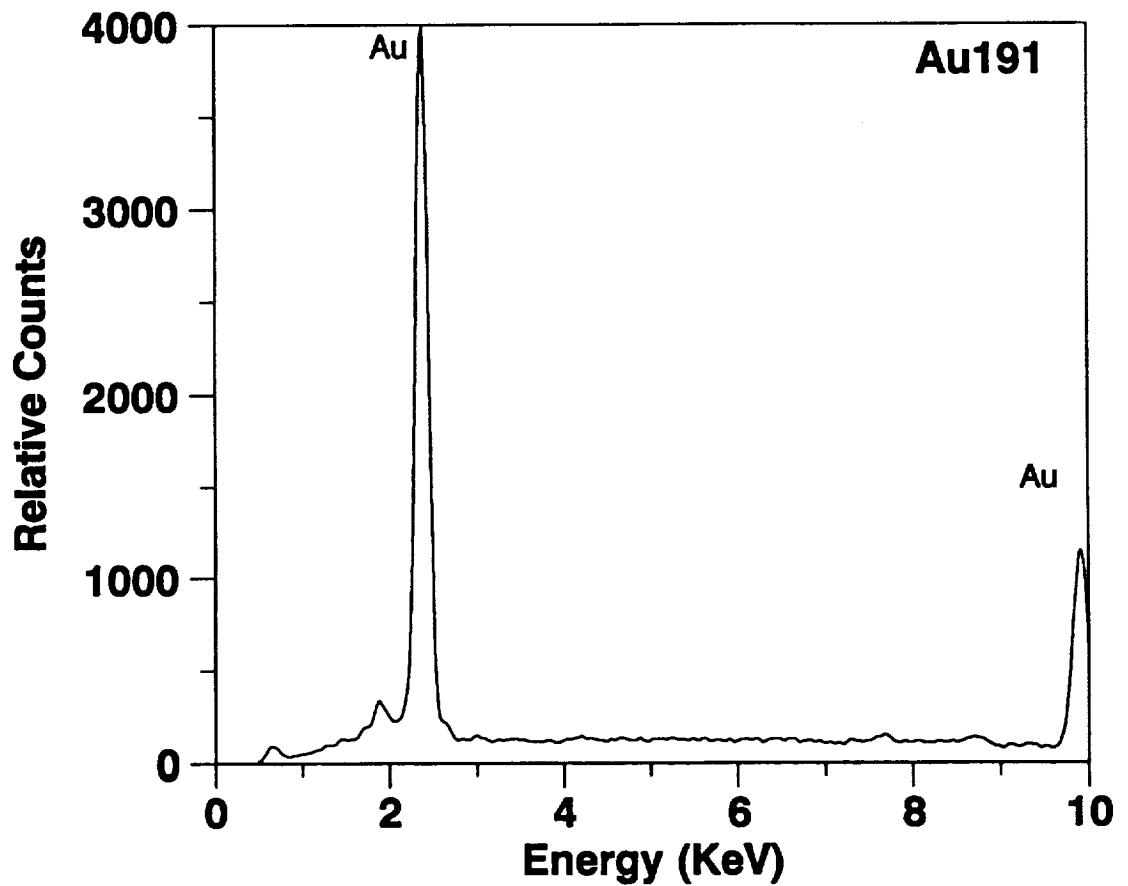


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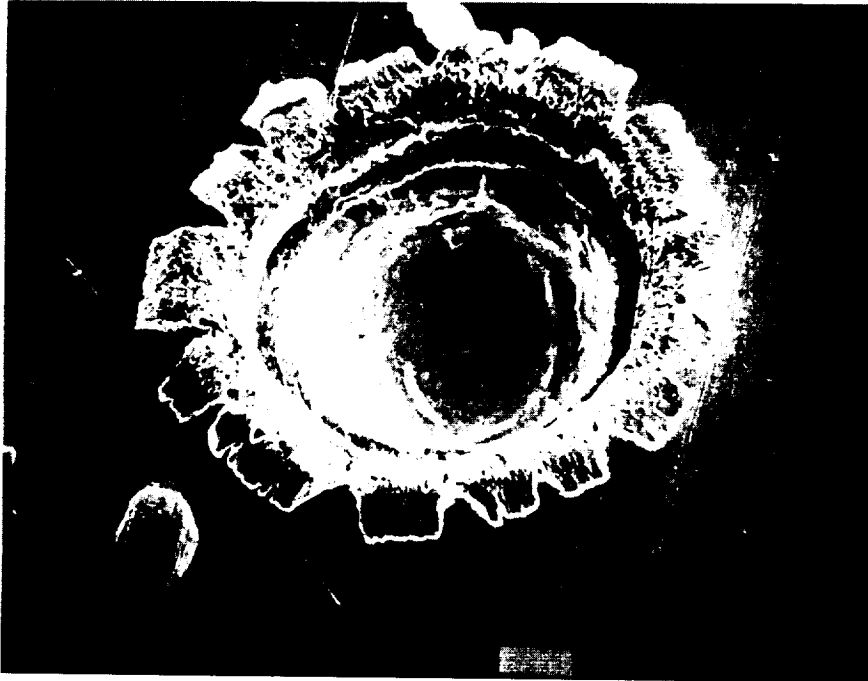


COMPONENT: EOOH
FEATURE: 191
CORE: LD-135
DIAMETER: 25 μm
ORIGIN: Unknown

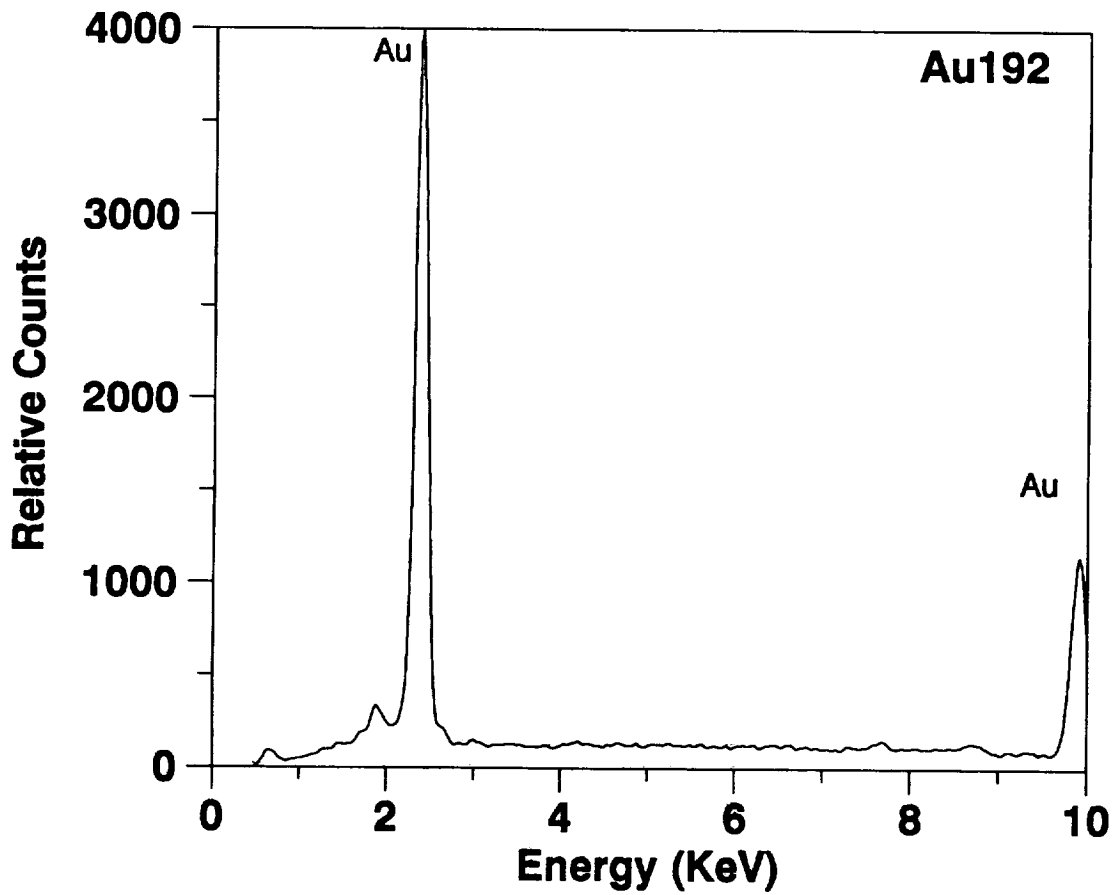


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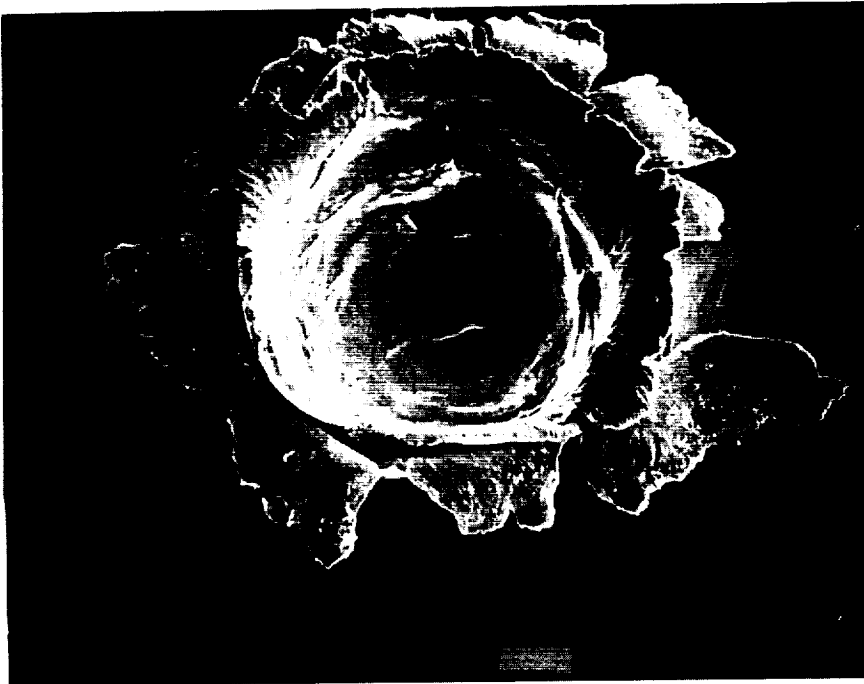


COMPONENT: EOOH
FEATURE: 192
CORE: LD-152
DIAMETER: 55 μ m
ORIGIN: Unknown

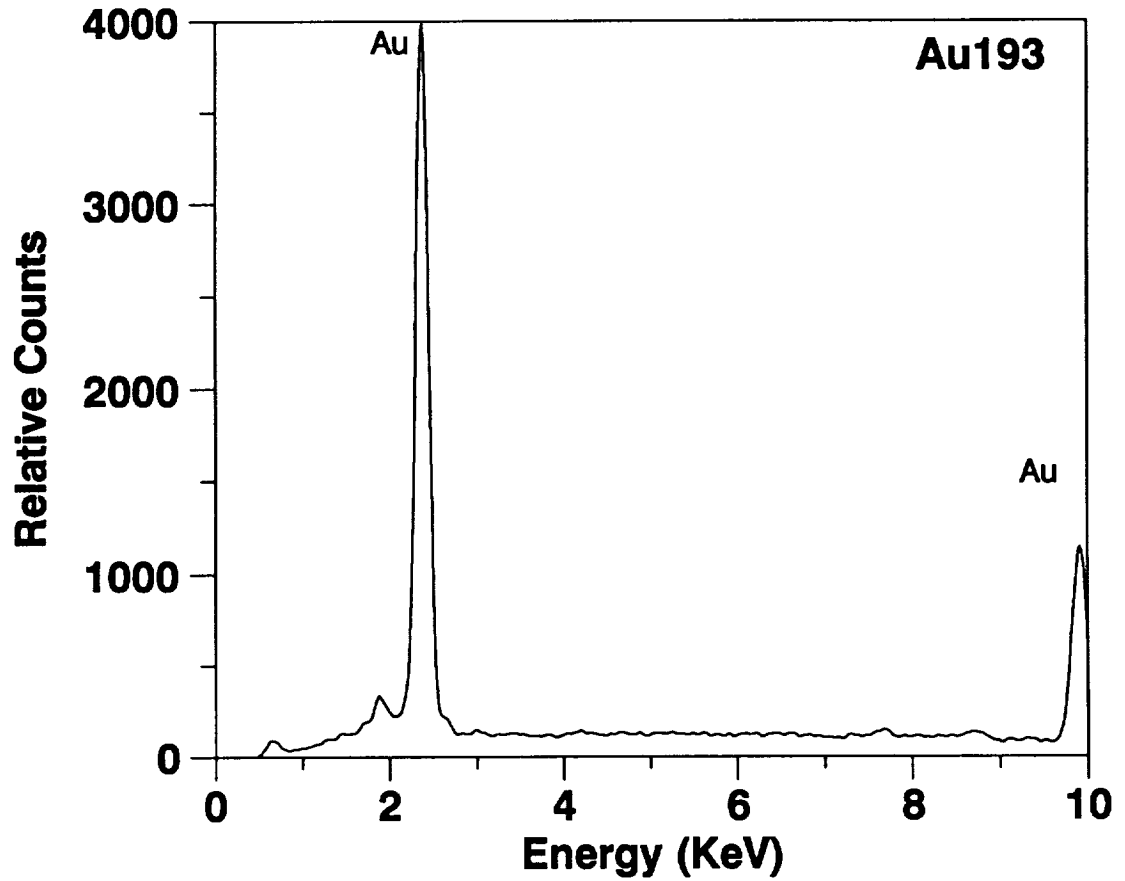


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COMPONENT: EOOH
FEATURE: 193
CORE: LD-155
DIAMETER: 100 μ m
ORIGIN: Unknown



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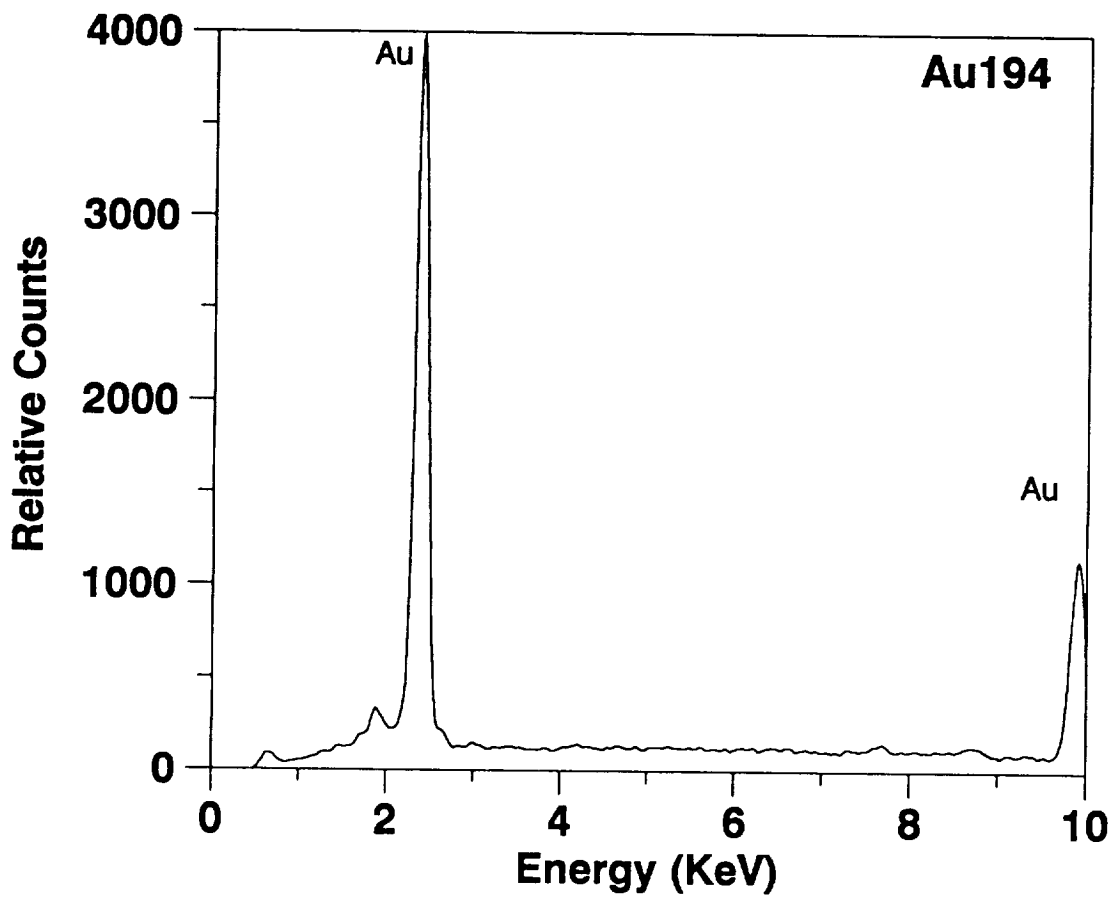
COMPONENT: EOOH

FEATURE: 194

CORE: LD-153

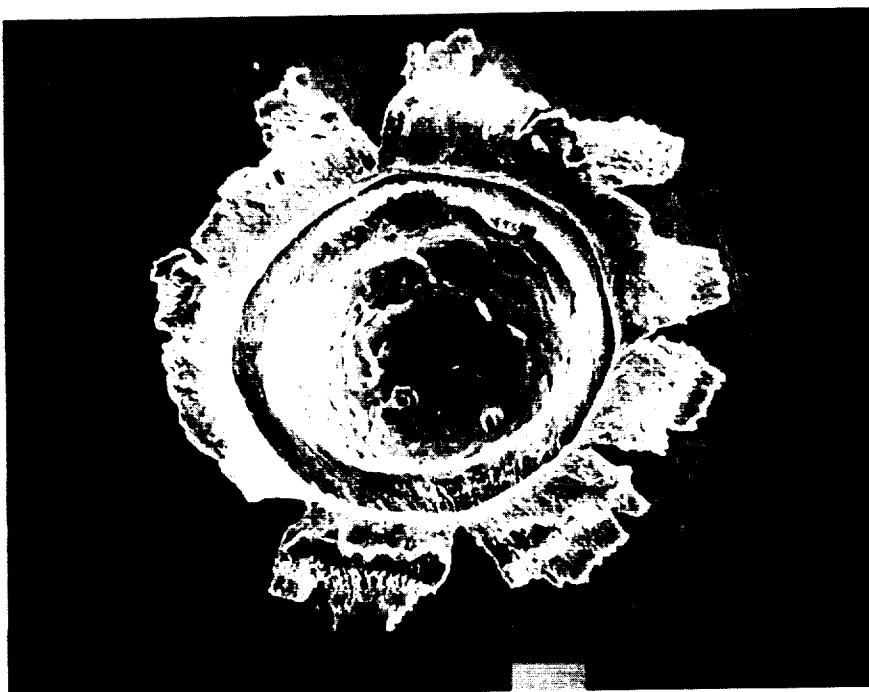
DIAMETER: 55 μ m

ORIGIN: Unknown

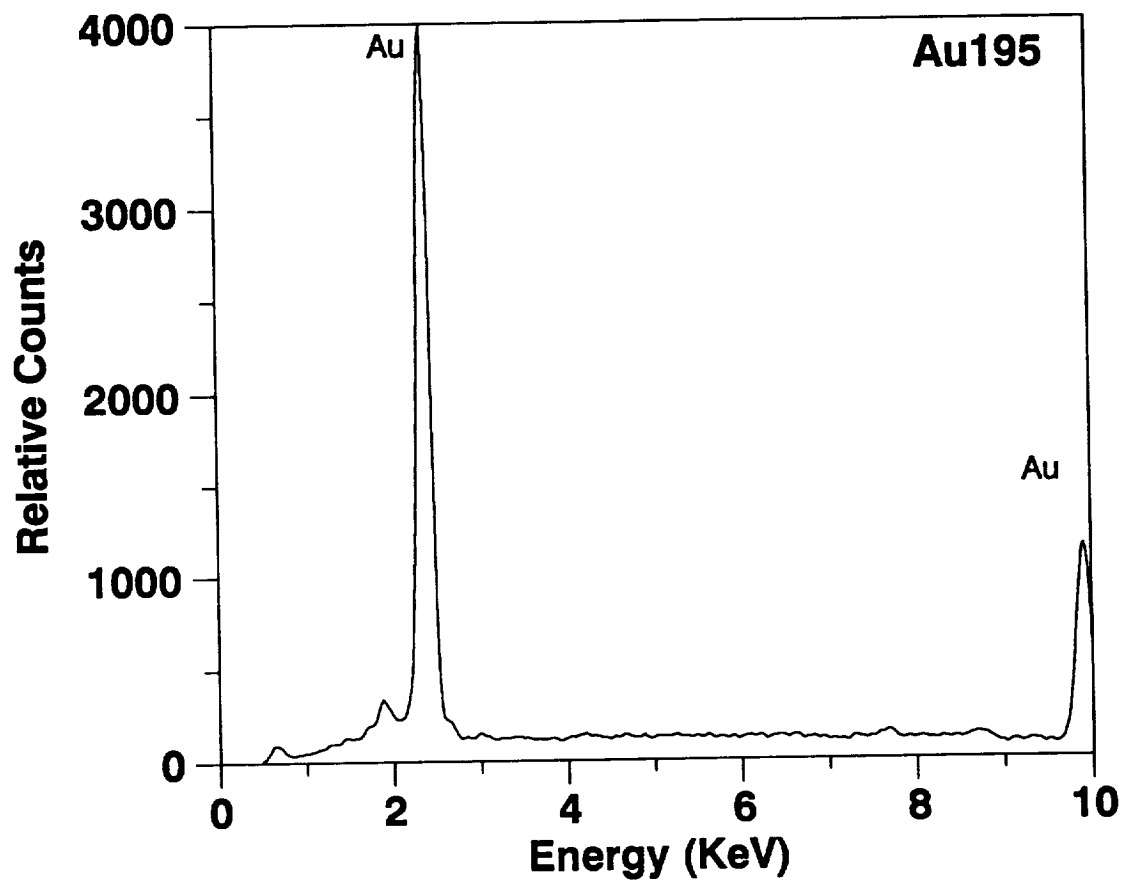


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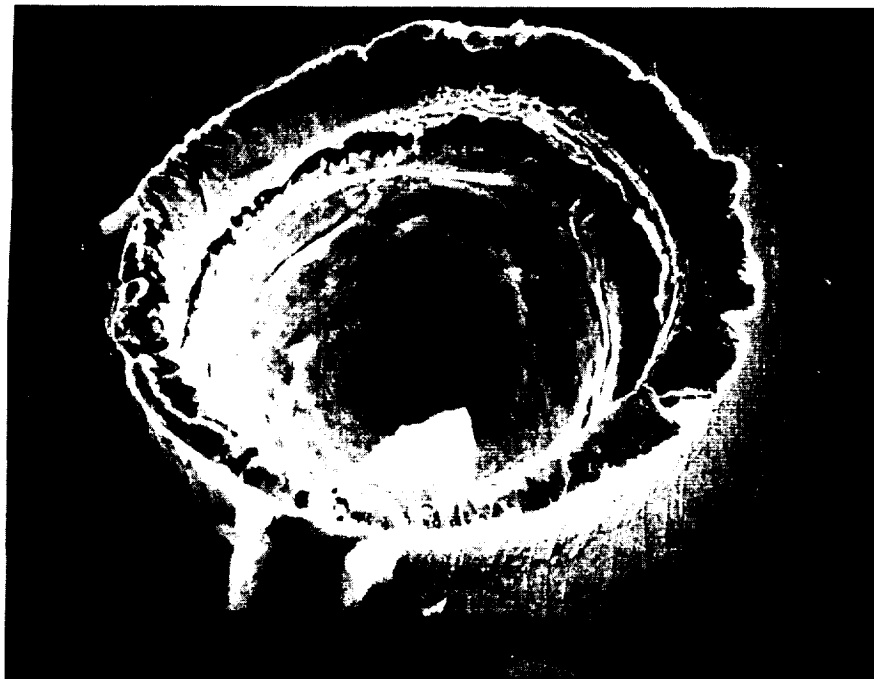


COMPONENT: EOOH
FEATURE: 195
CORE: LD-151
DIAMETER: 65 μm
ORIGIN: Unknown

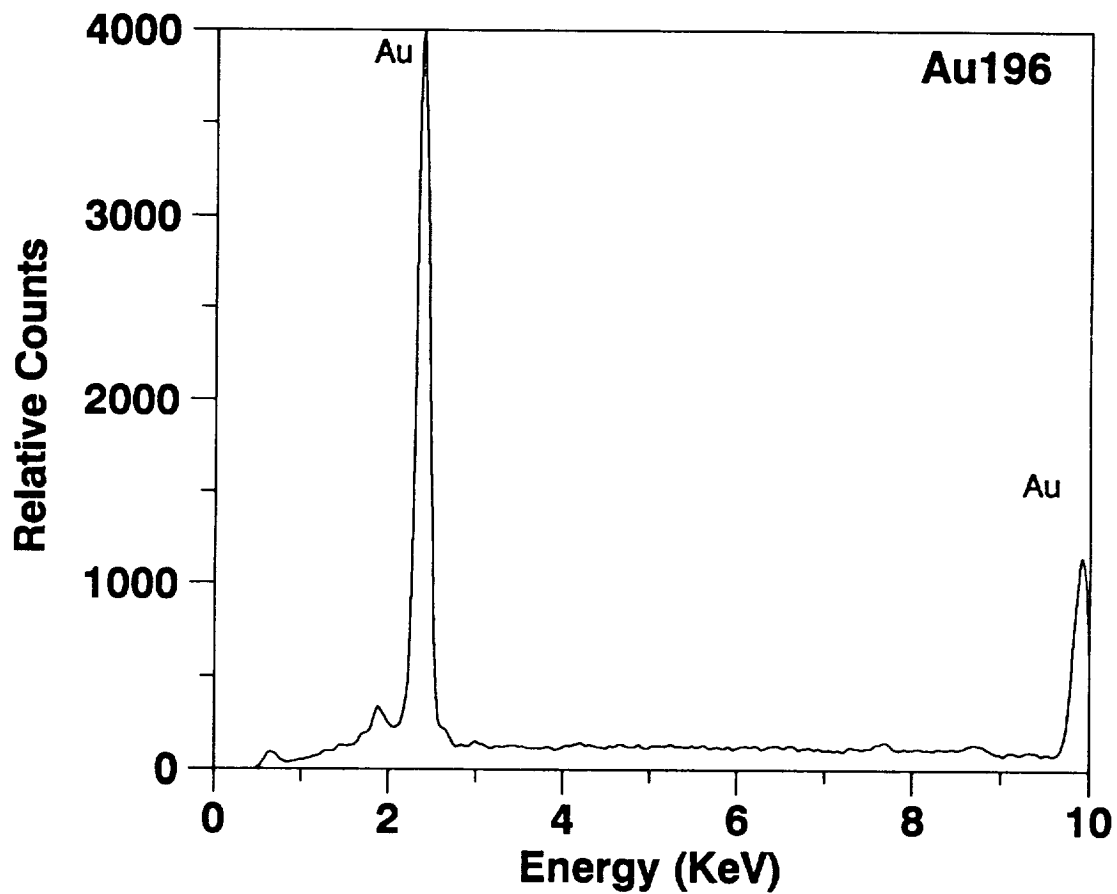


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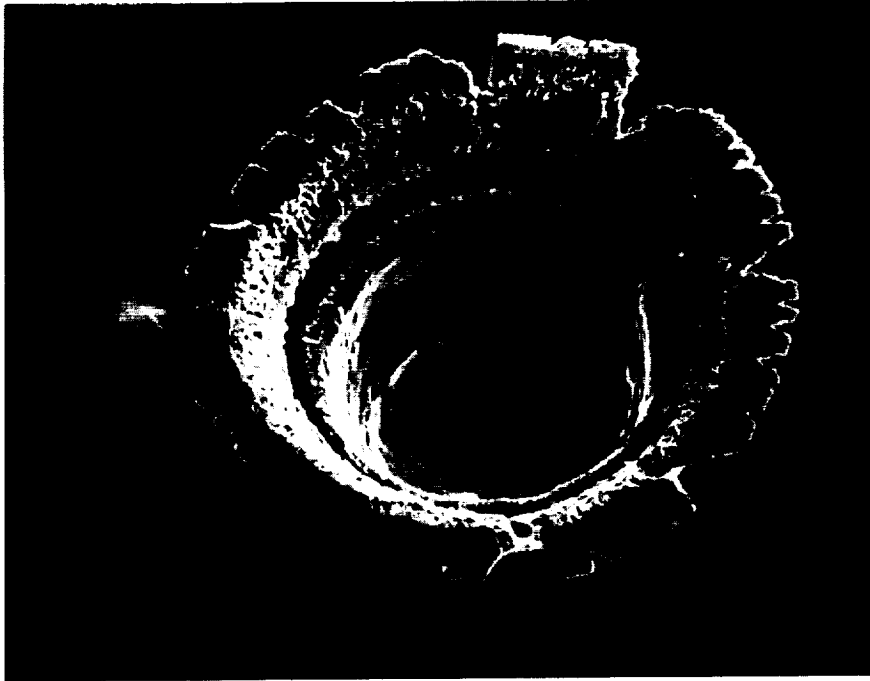


COMPONENT: EOOH
FEATURE: 196
CORE: LD-154
DIAMETER: 30 μ m
ORIGIN: Unknown



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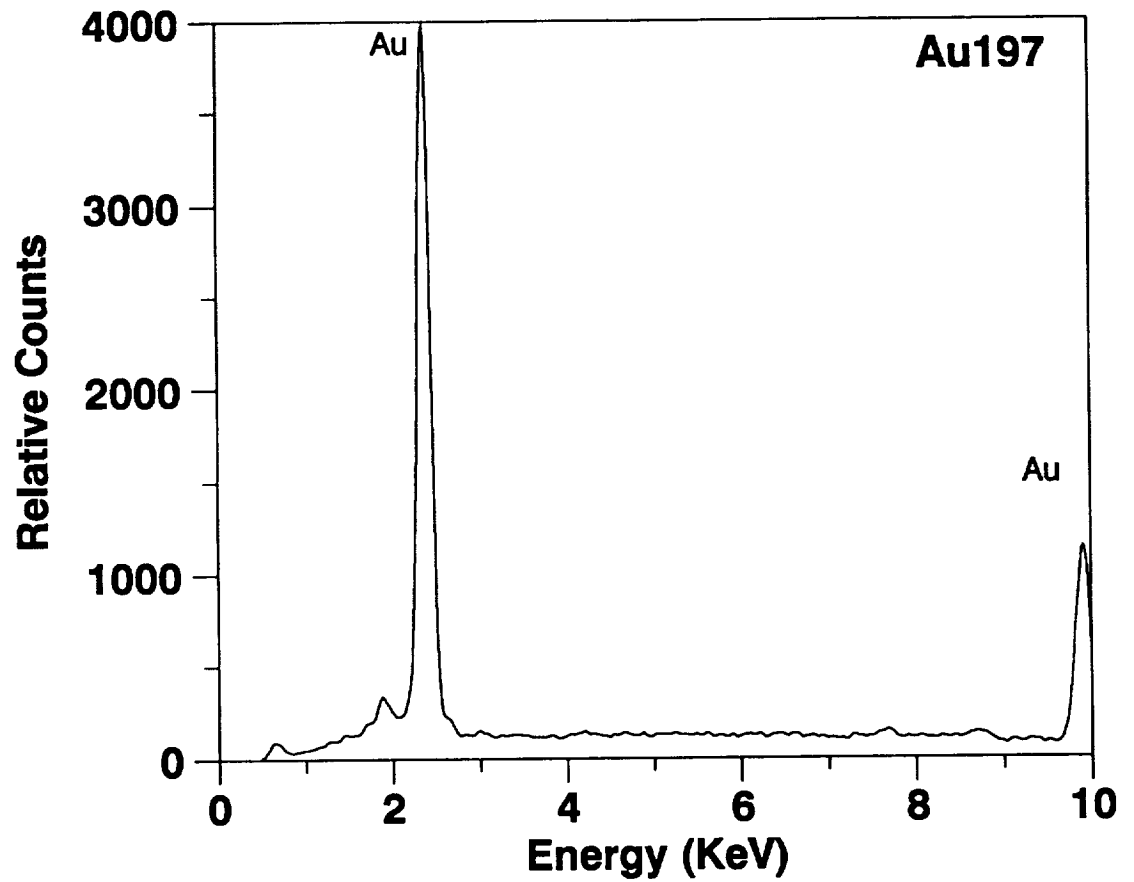
COMPONENT: EOOH

FEATURE: 197

CORE: LD-146

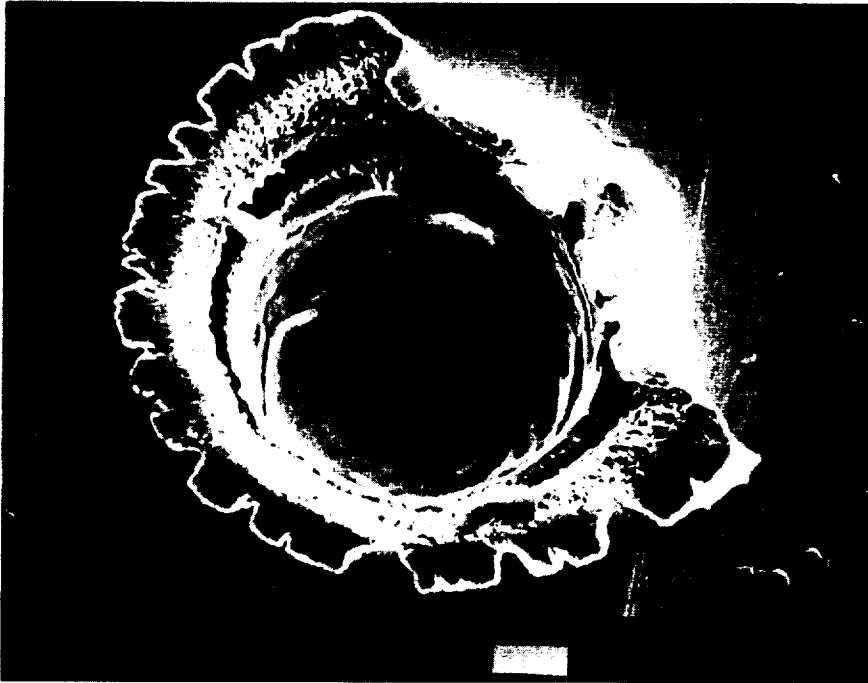
DIAMETER: 55 μm

ORIGIN: Unknown

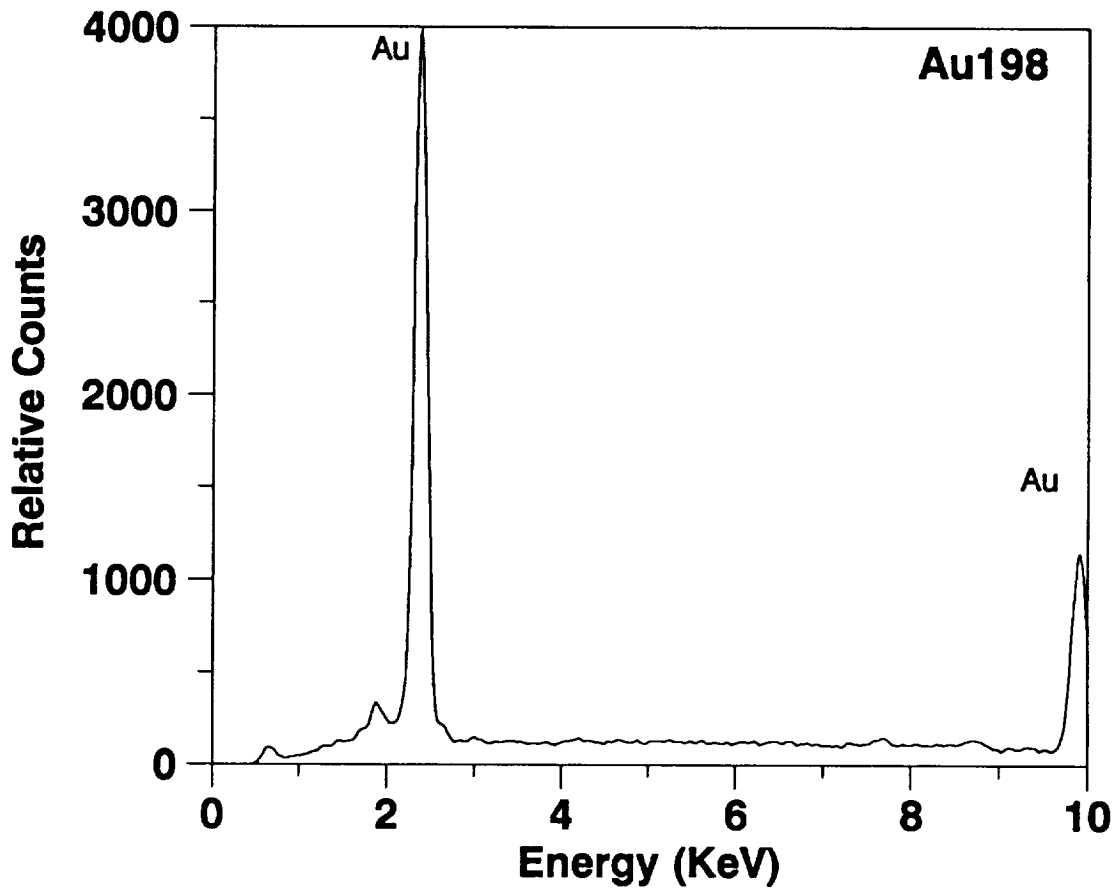


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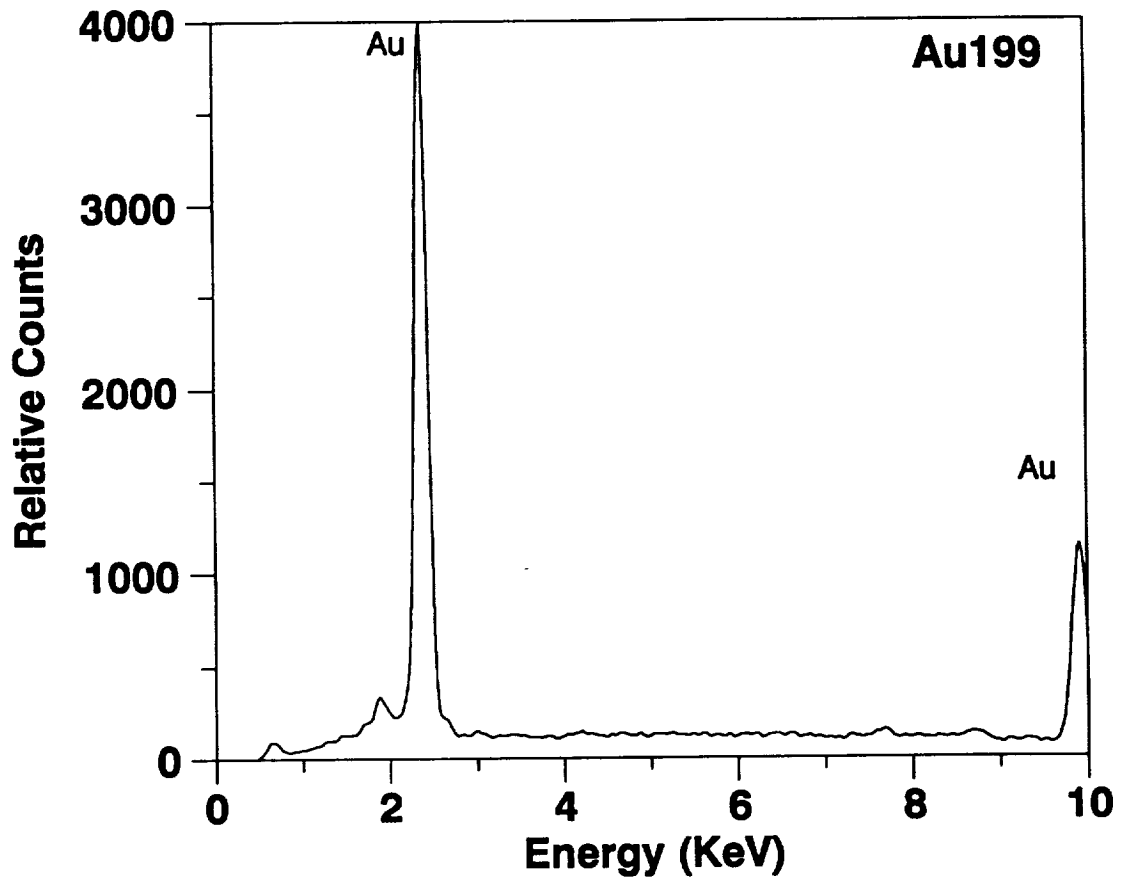


COMPONENT: EOOH
FEATURE: 198
CORE: LD-145
DIAMETER: 45 μ m
ORIGIN: Unknown



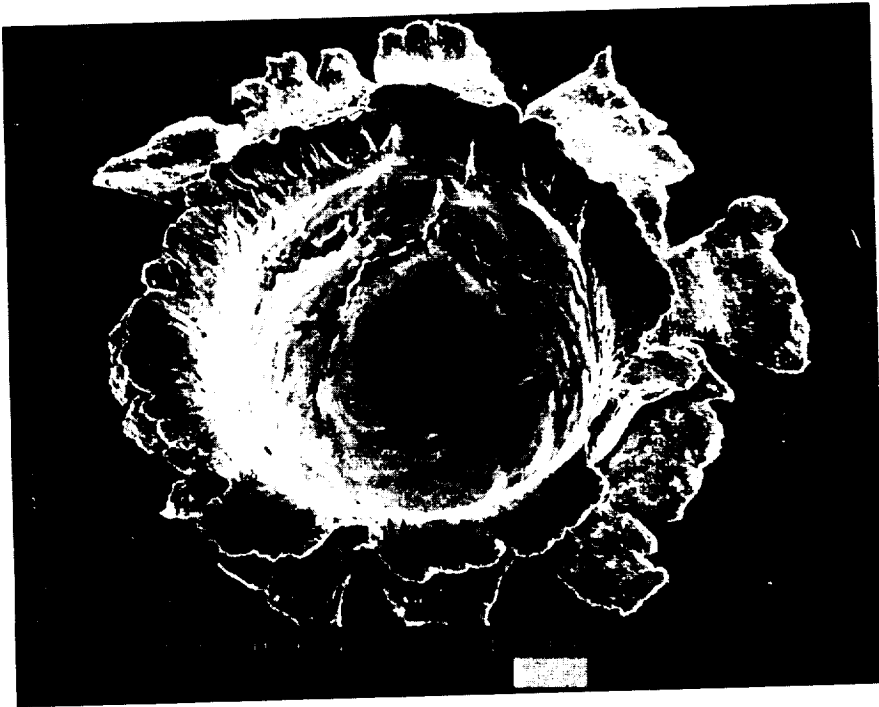


COMPONENT: EOOH
FEATURE: 199
CORE: LD-144
DIAMETER: 20 μ m
ORIGIN: Unknown

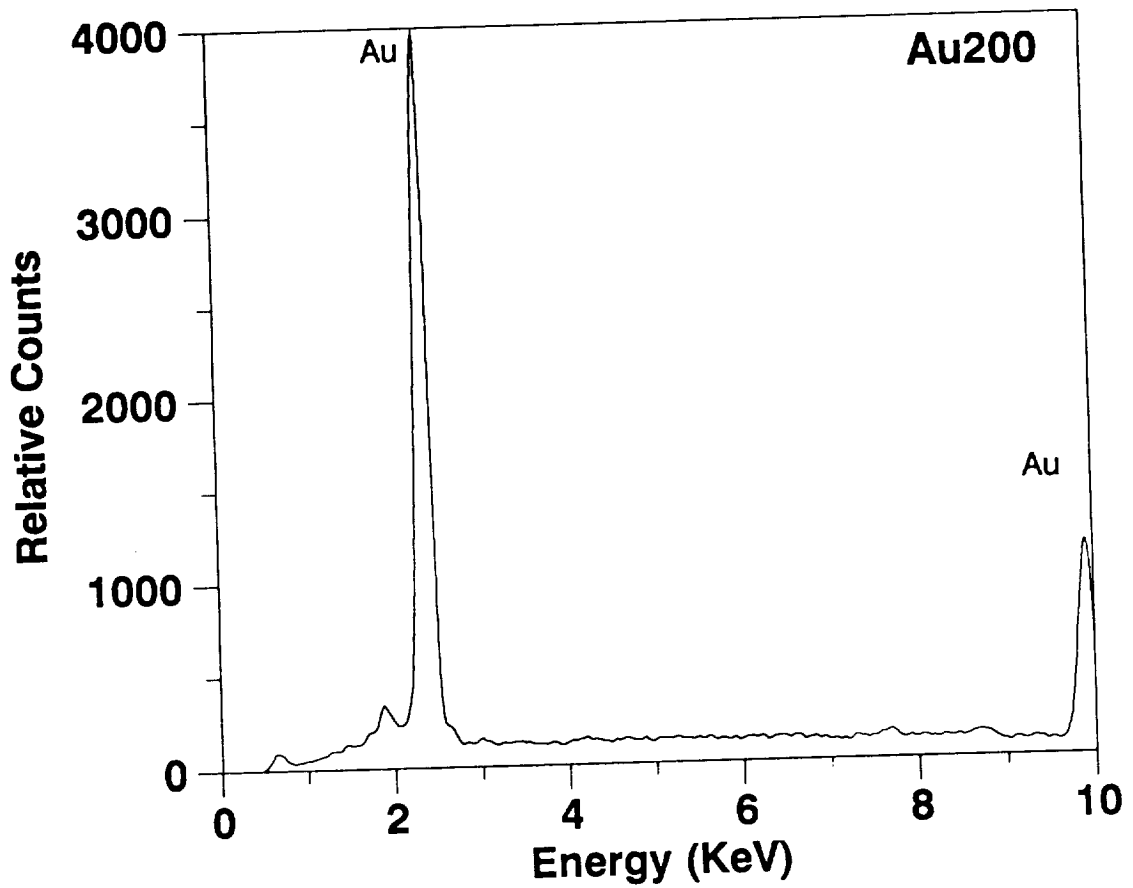


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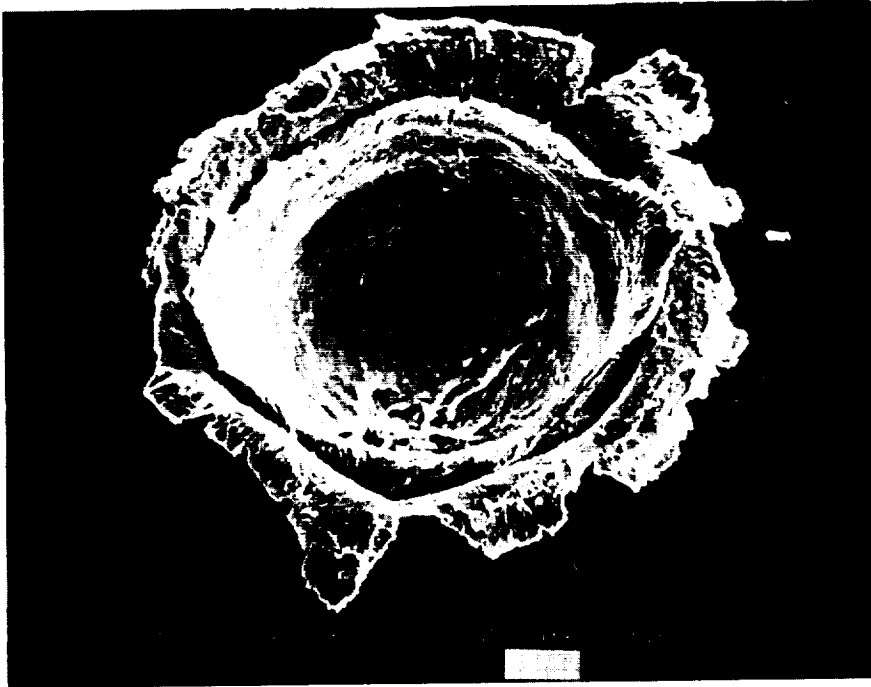


COMPONENT: EOOH
FEATURE: 200
CORE: LD-143
DIAMETER: 95 μm
ORIGIN: Unknown

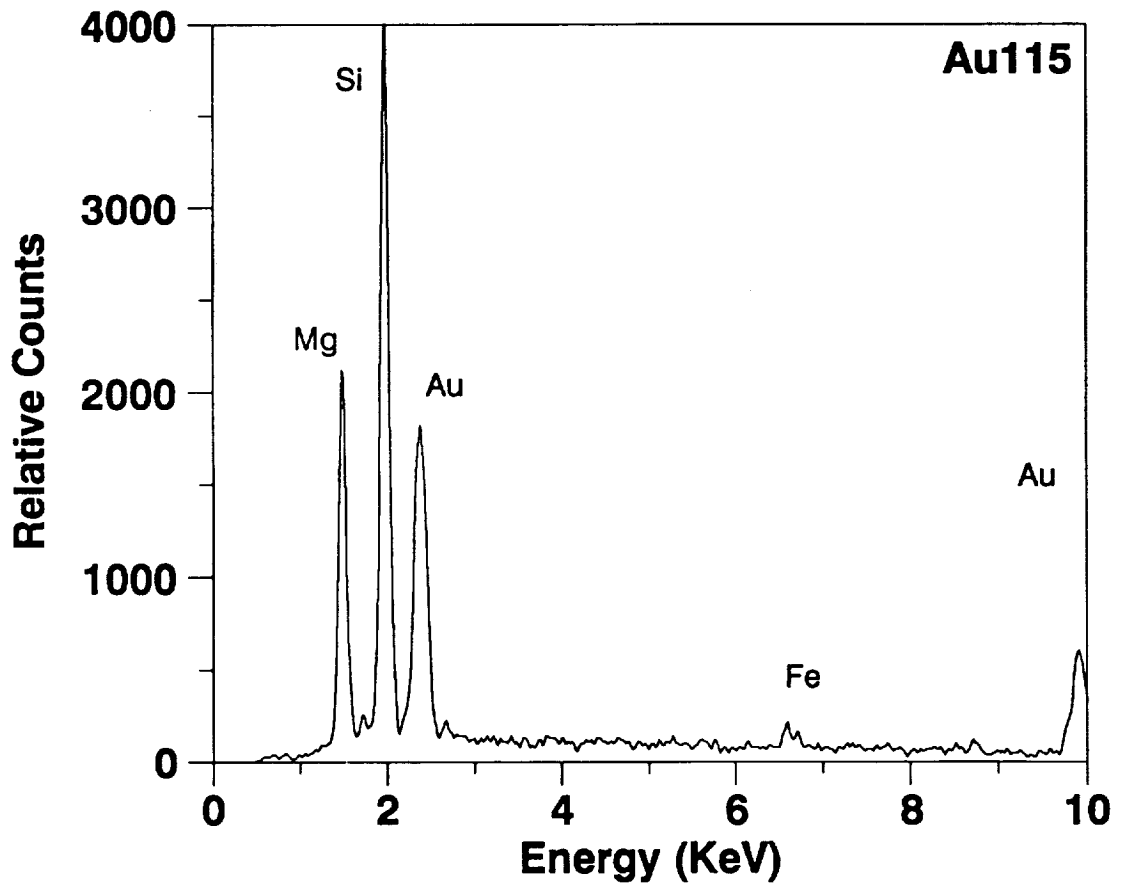


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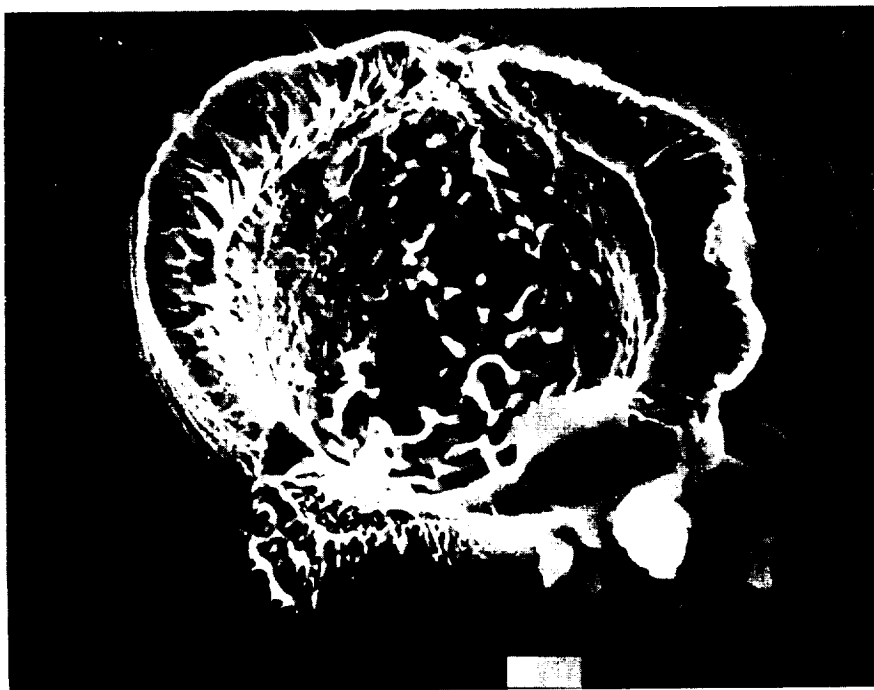


COMPONENT: EOOH
FEATURE: 201
CORE: LD-150
DIAMETER: 55 μ m
ORIGIN: Natural

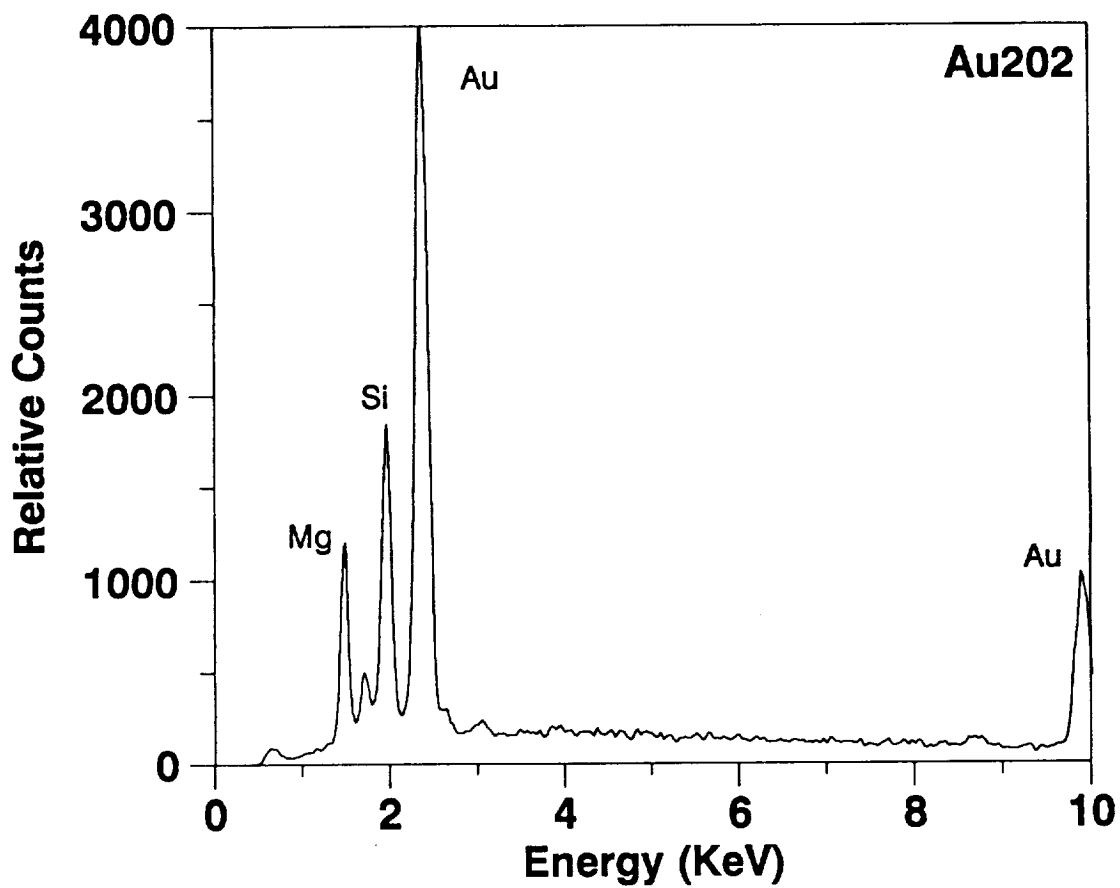


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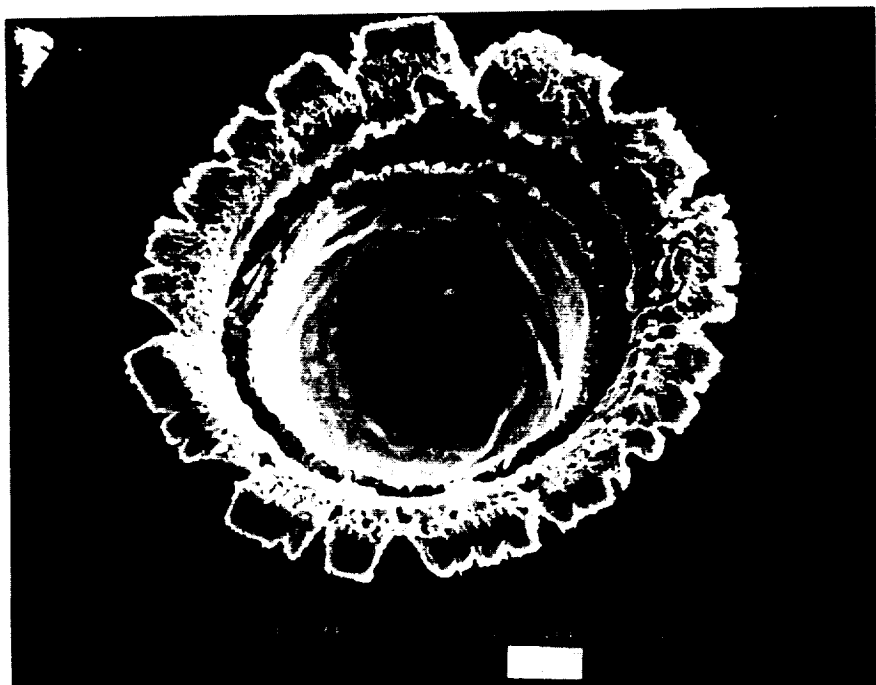


COMPONENT: EOOH
FEATURE: 202
CORE: LD-141
DIAMETER: 20 μ m
ORIGIN: Natural

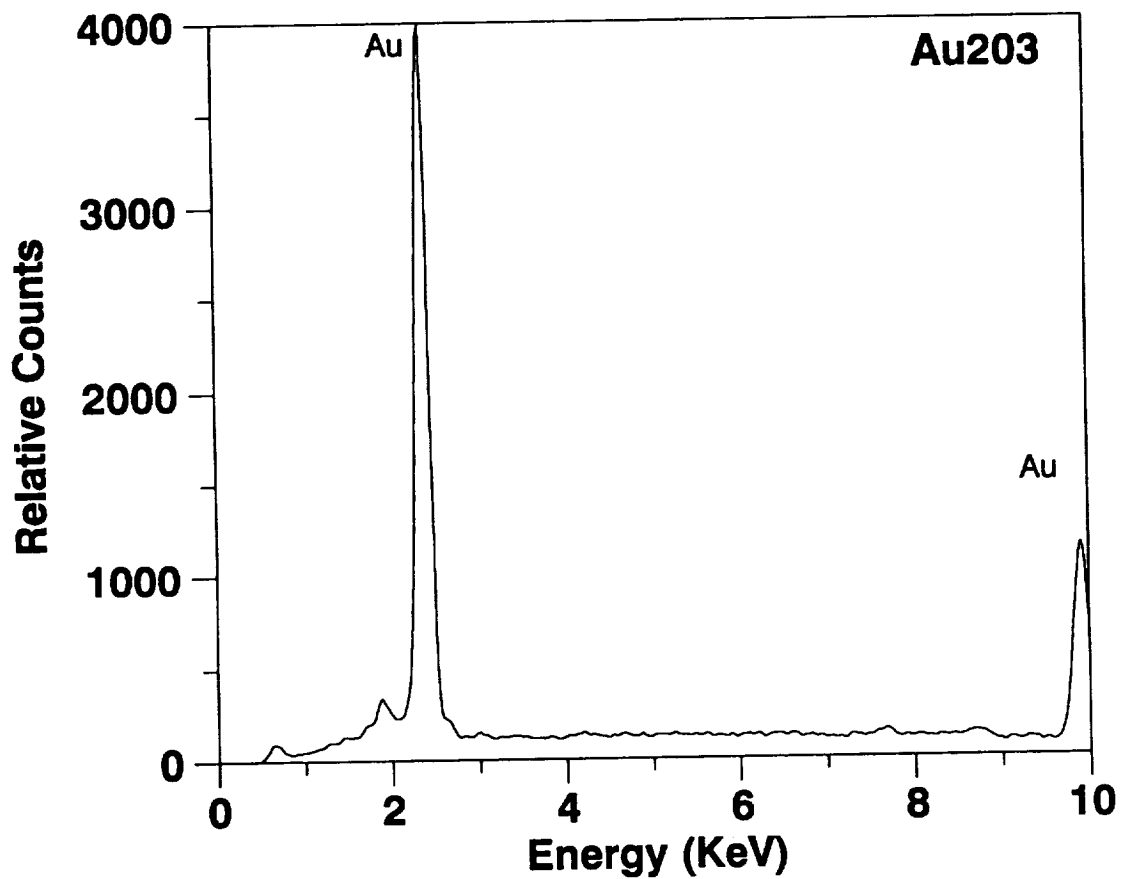


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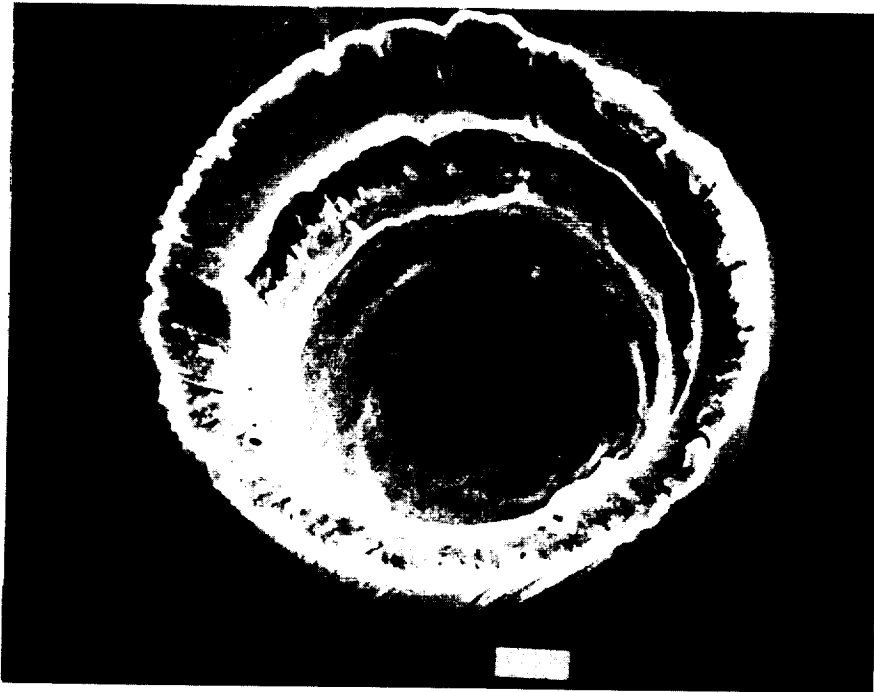


COMPONENT: EOOH
FEATURE: 203
CORE: LD-149
DIAMETER: 30 μm
ORIGIN: Unknown

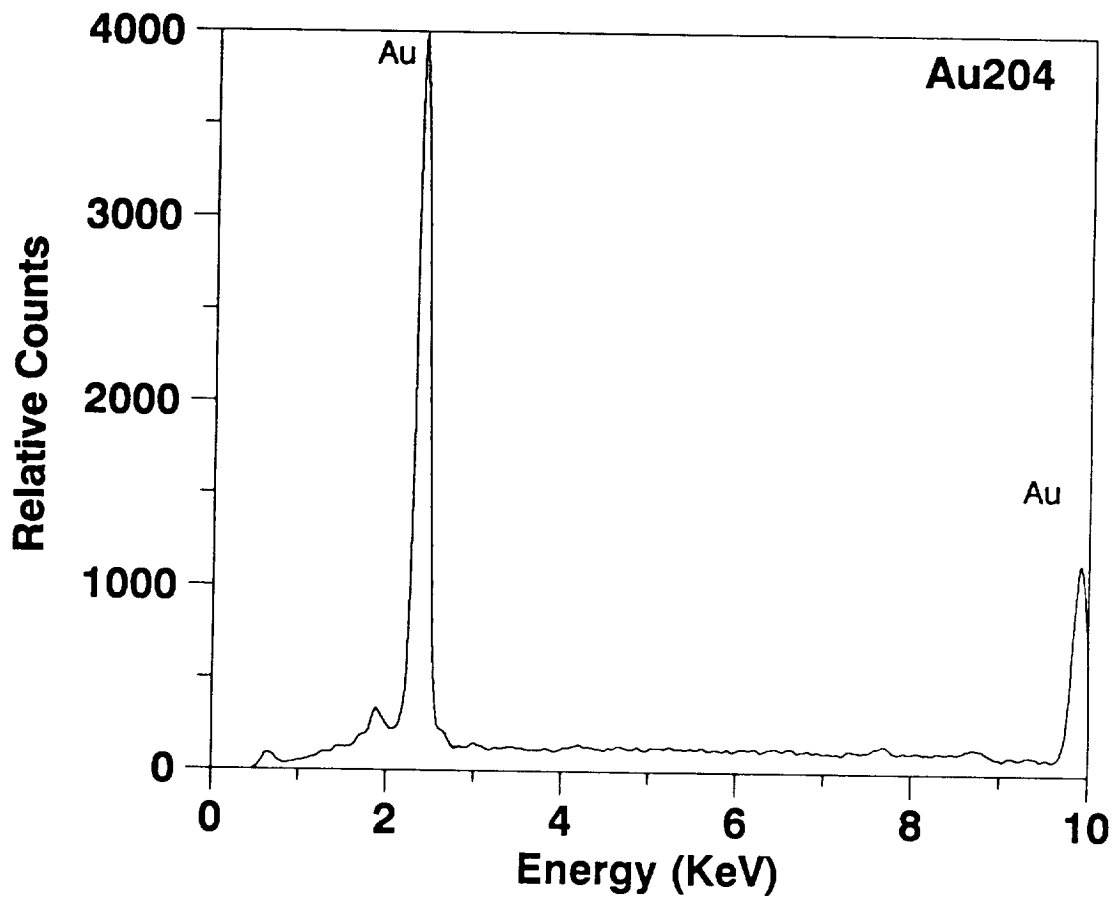


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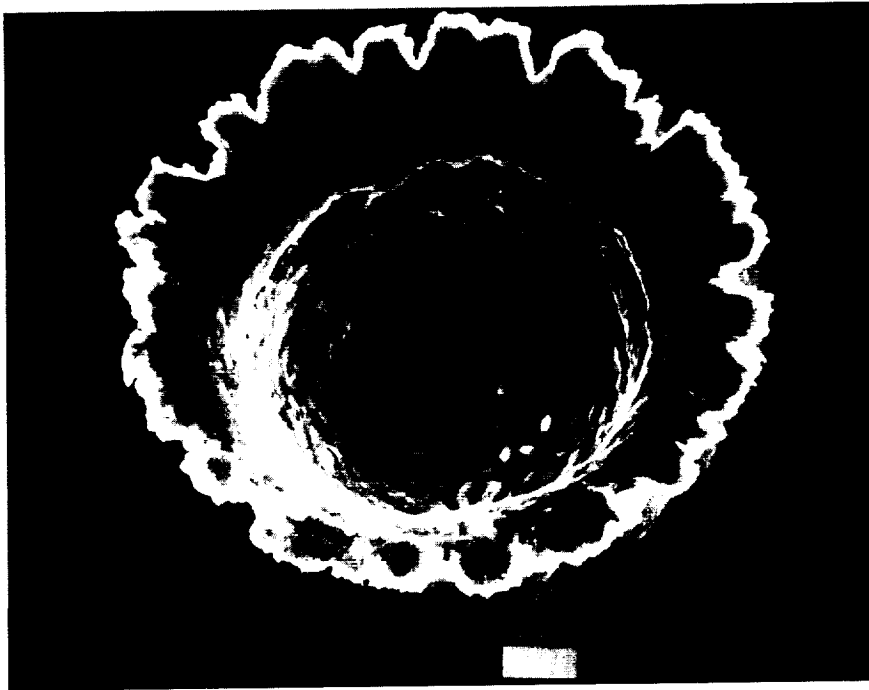


COMPONENT: EOOH
FEATURE: 204
CORE: LD-142
DIAMETER: 15 μm
ORIGIN: Unknown

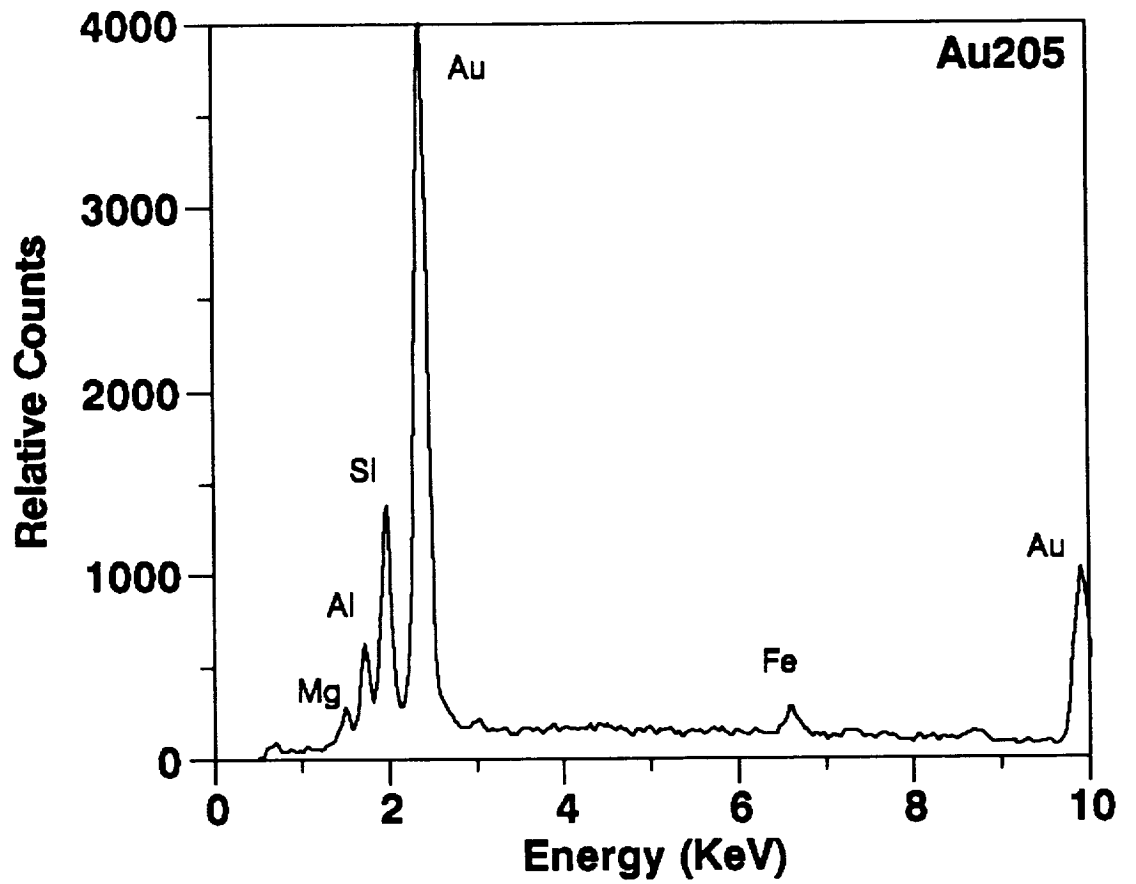


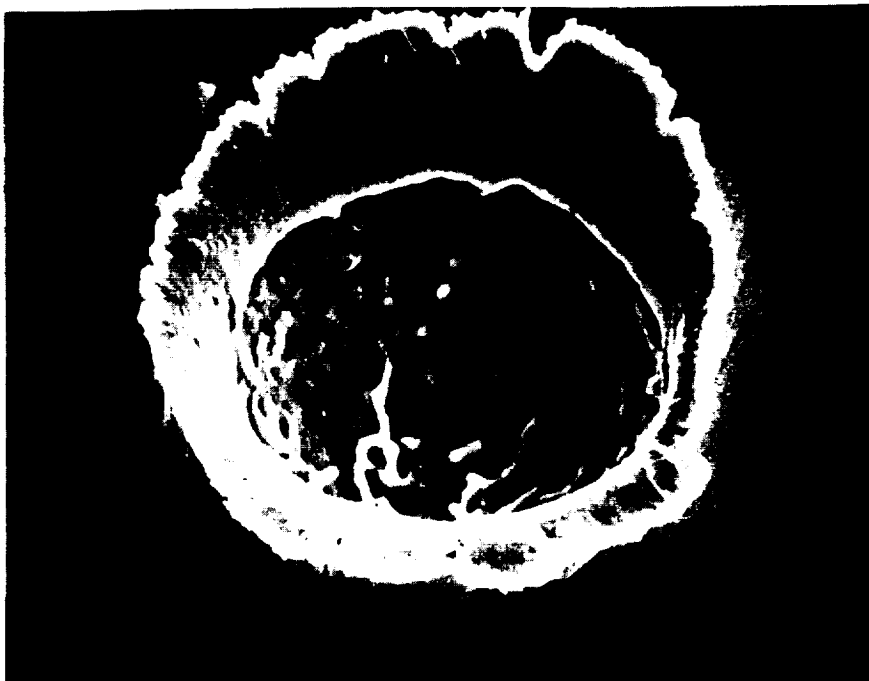
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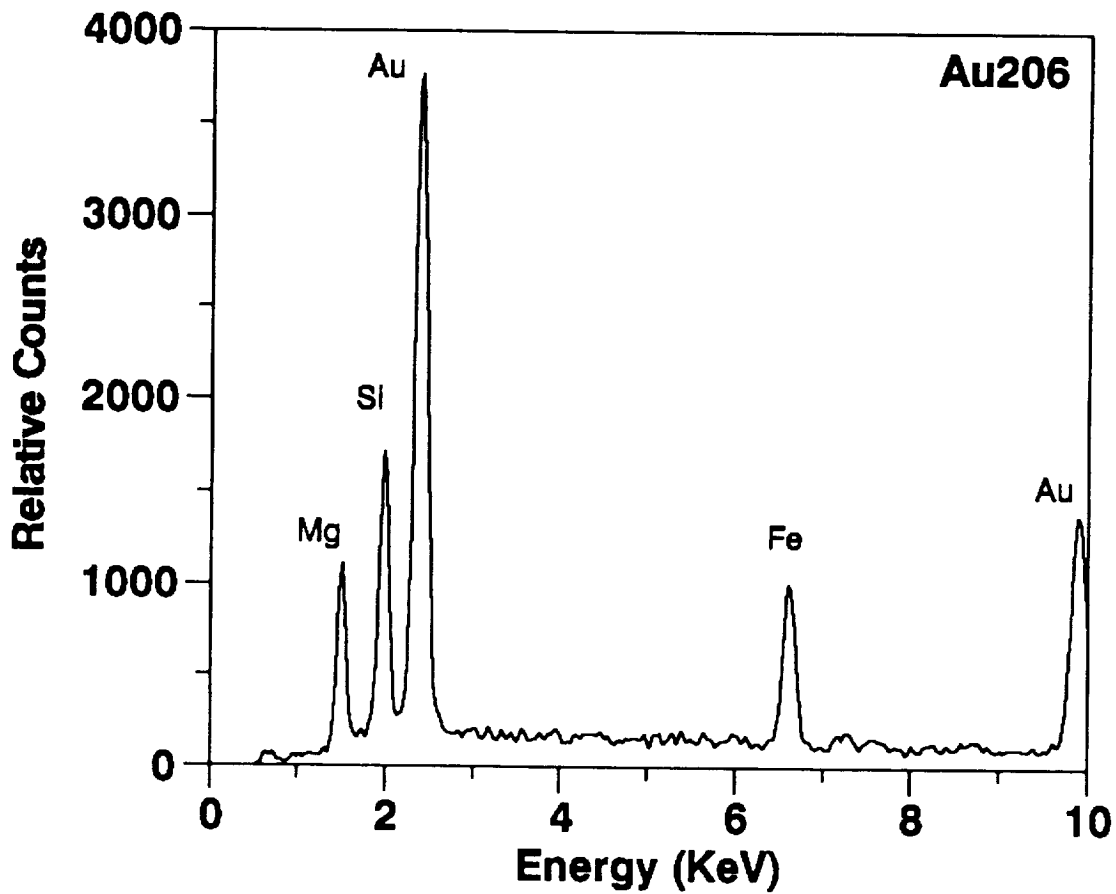


COMPONENT: EOOE
FEATURE: 205
CORE: LD-137
DIAMETER: 15 μ m
ORIGIN: Natural



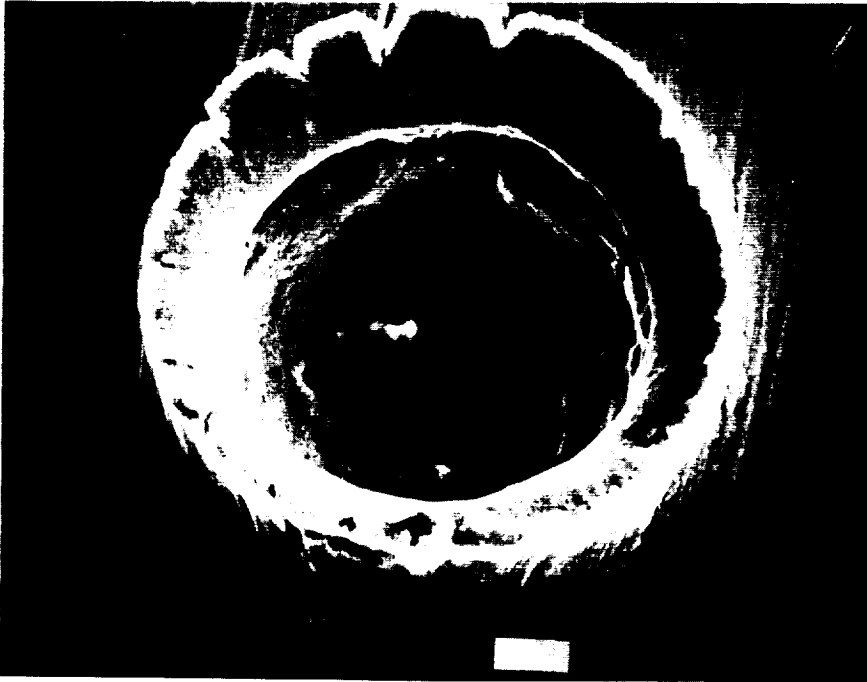


COMPONENT: EOOE
FEATURE: 208
CORE: LD-138
DIAMETER: 10 μ m
ORIGIN: Natural

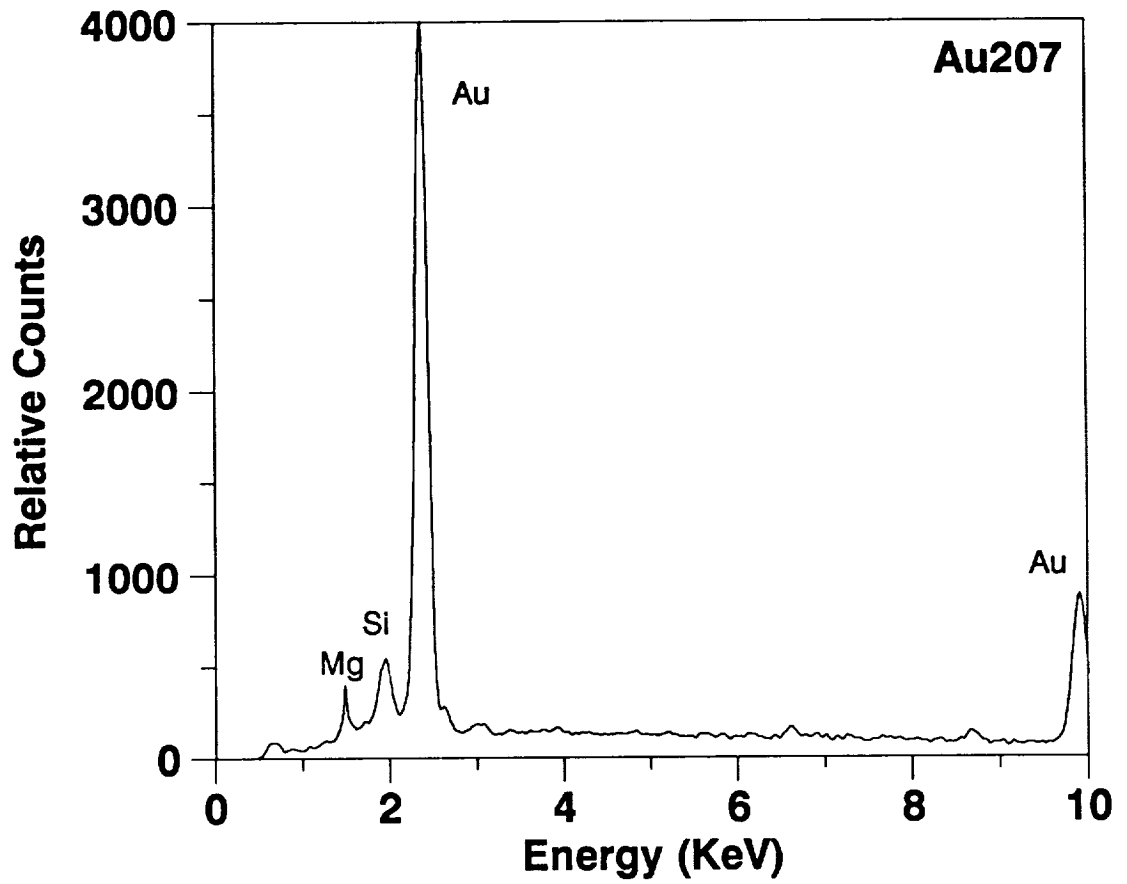


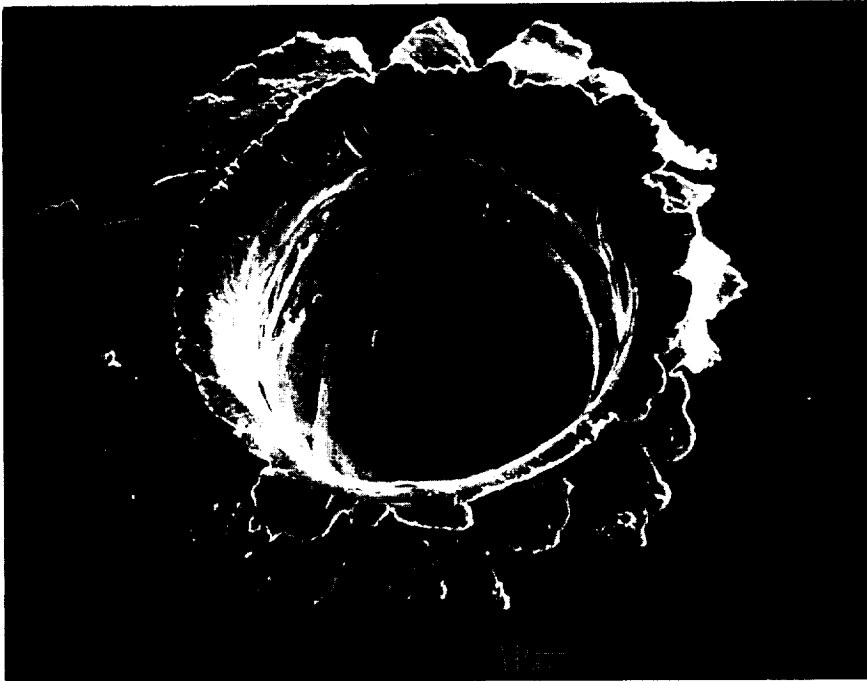
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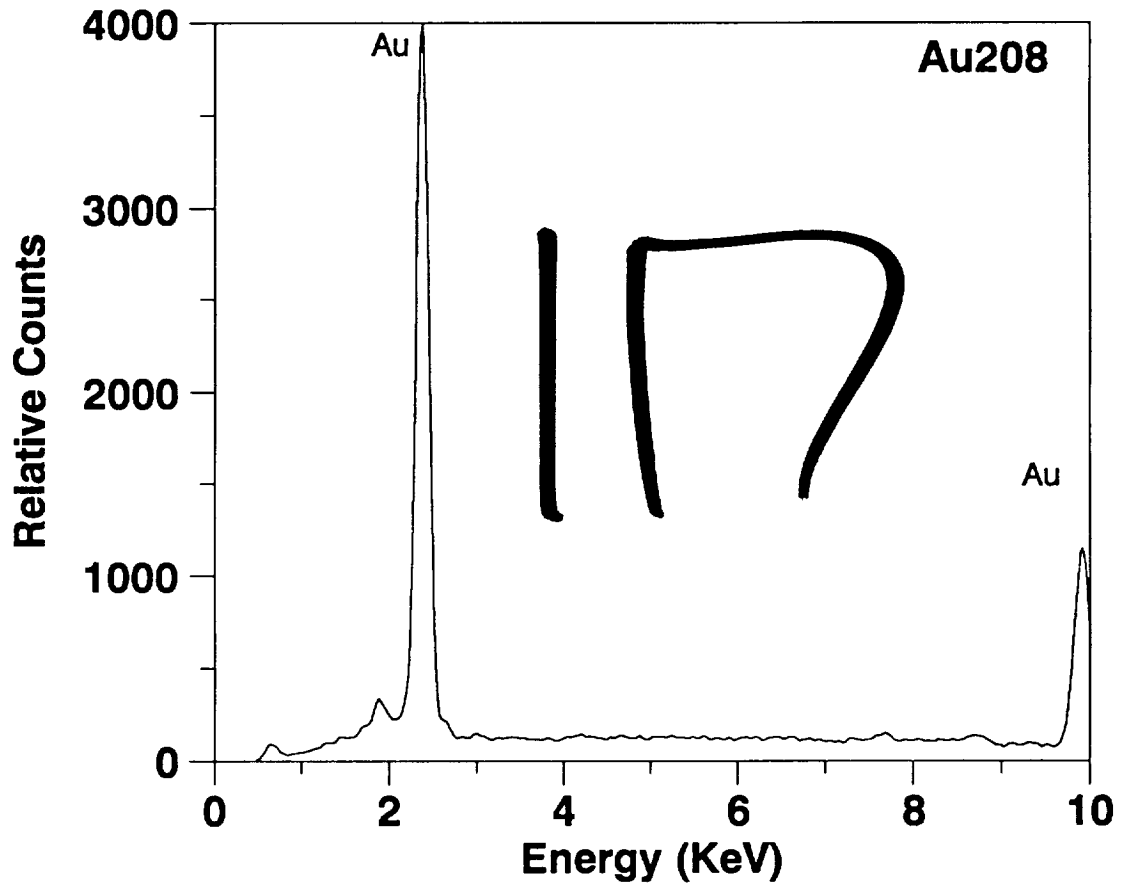


COMPONENT: EOOH
FEATURE: 207
CORE: LD-147
DIAMETER: 15 μm
ORIGIN: Natural



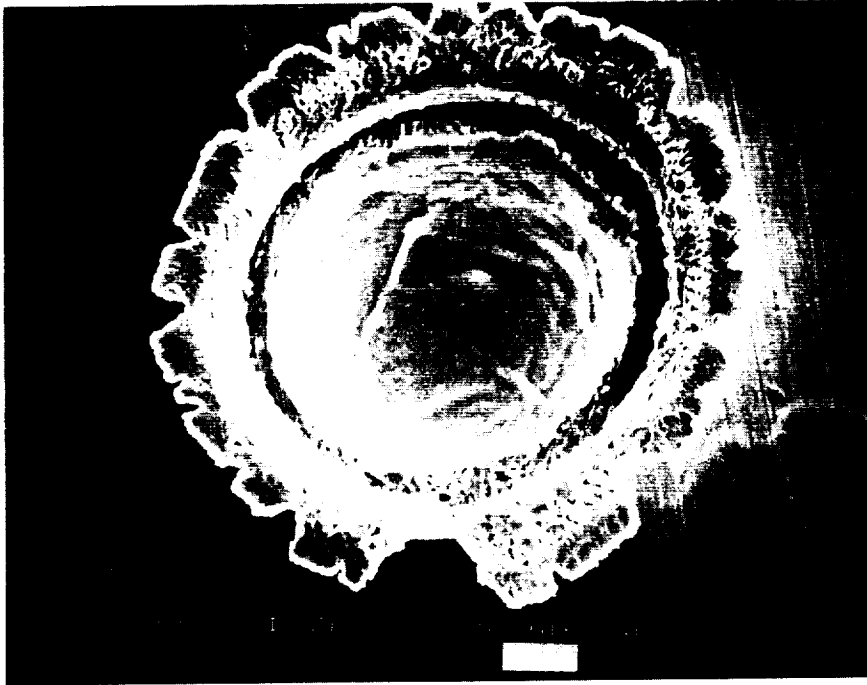


COMPONENT: EOOH
FEATURE: 208
CORE: LD-139
DIAMETER: 65 μm
ORIGIN: Unknown



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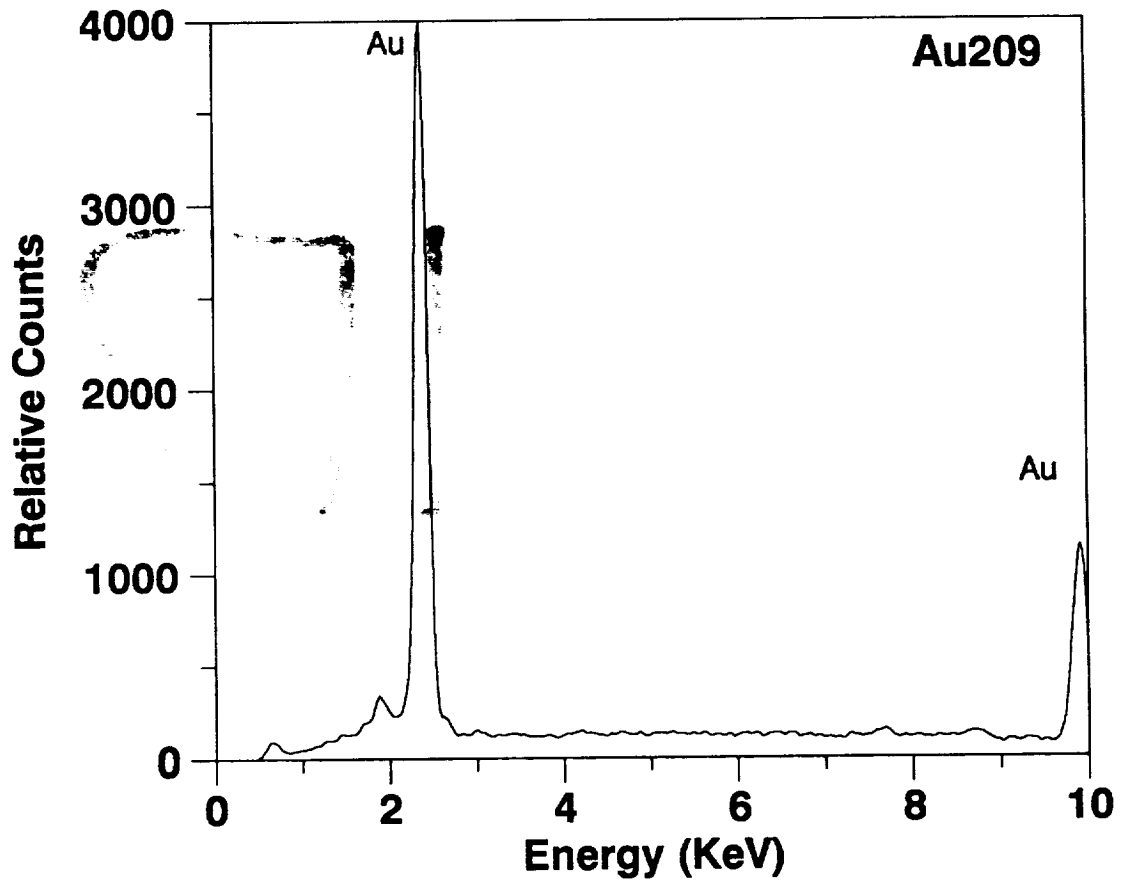
COMPONENT: EOOH

FEATURE: 209

CORE: LD-140

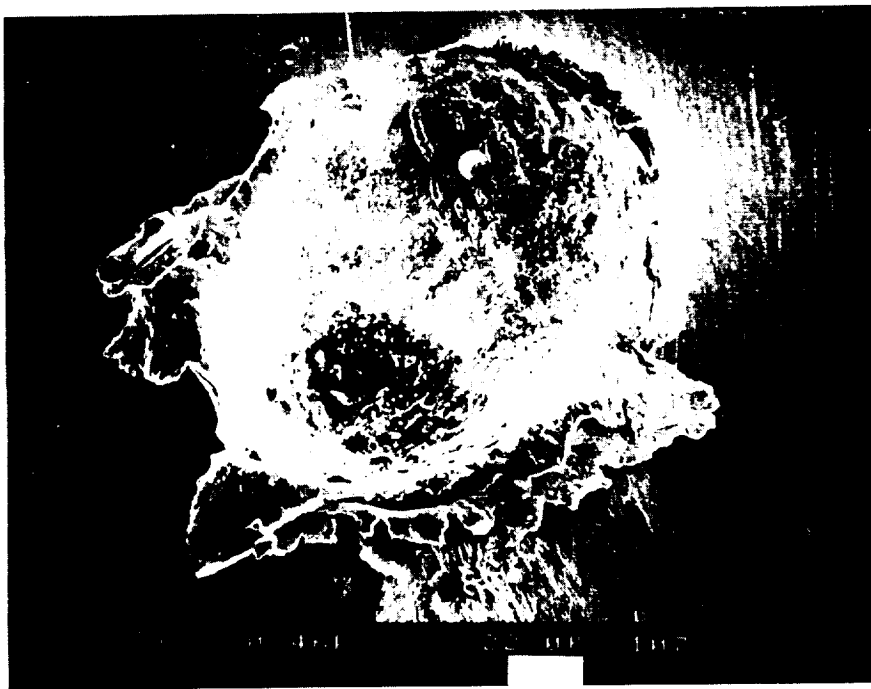
DIAMETER: 30 μm

ORIGIN: Unknown

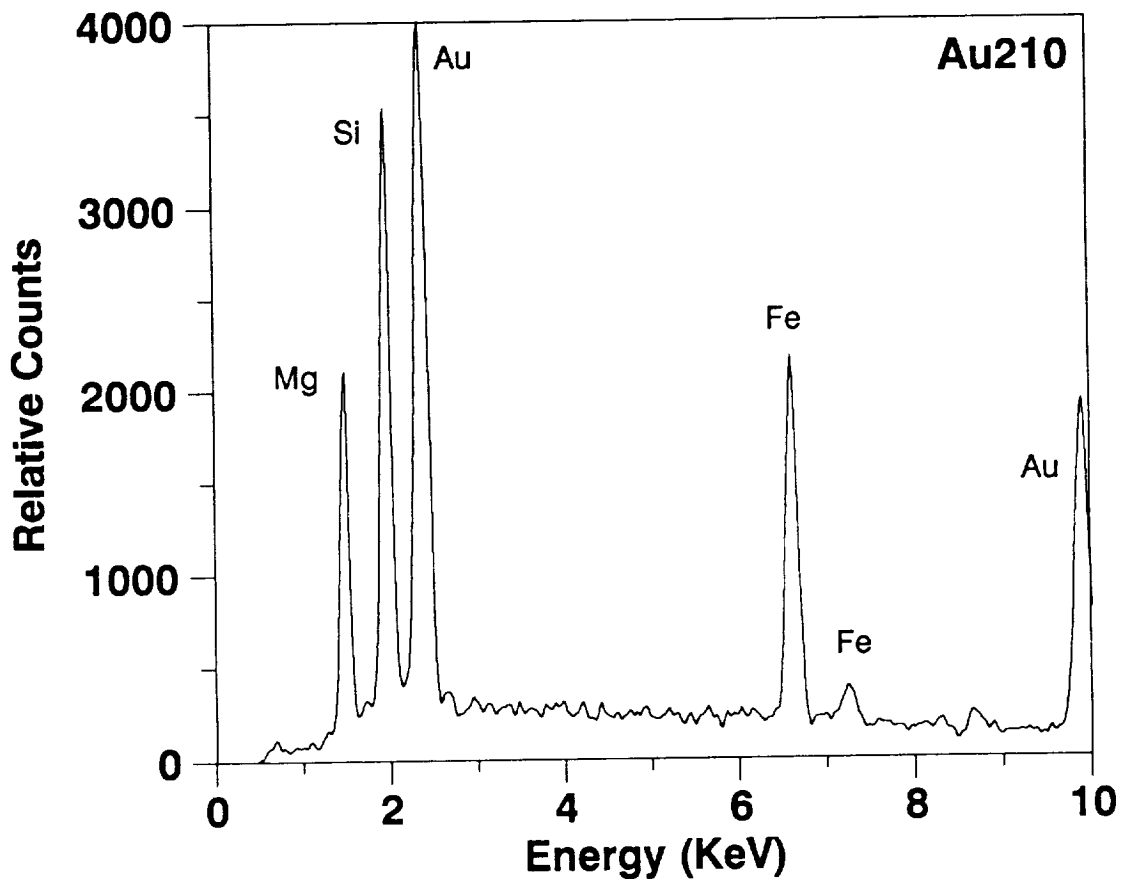


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COMPONENT: EOOH
FEATURE: 210
CORE: LD-148
DIAMETER: 115 μ m
ORIGIN: Natural

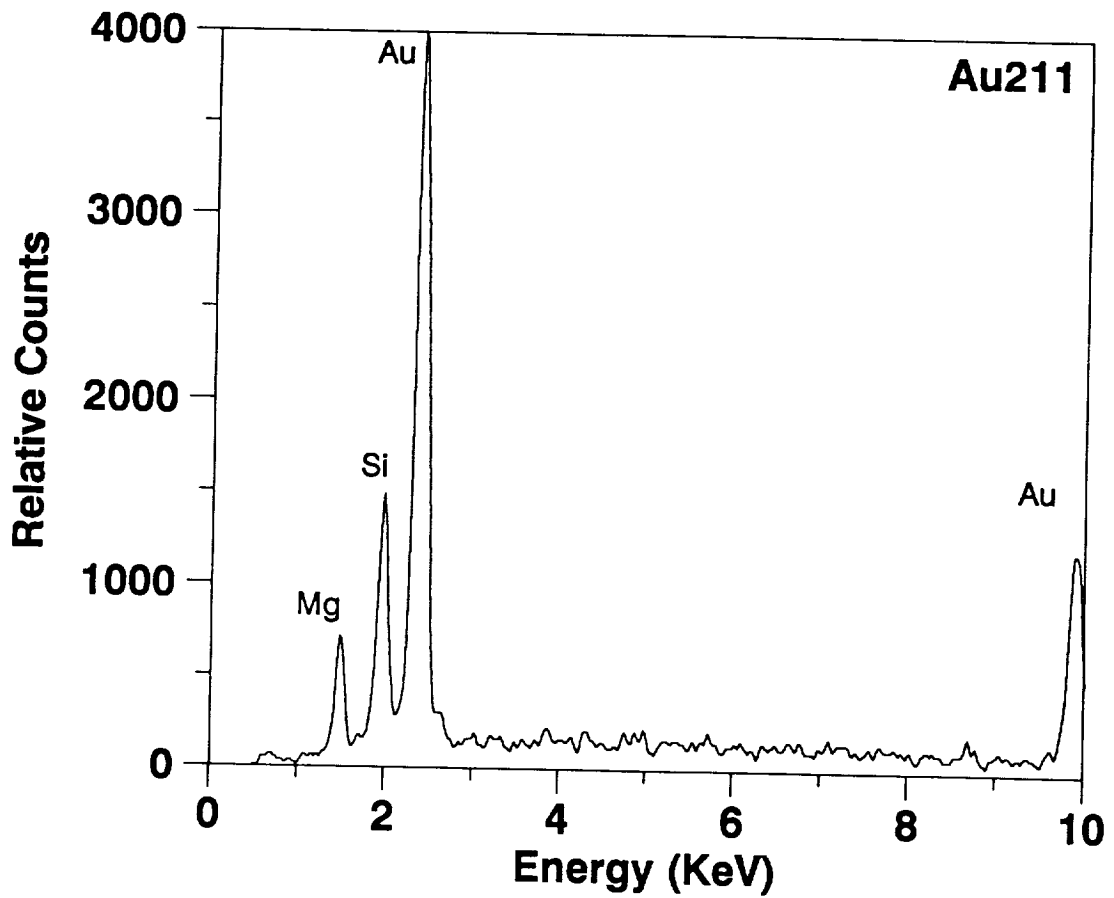


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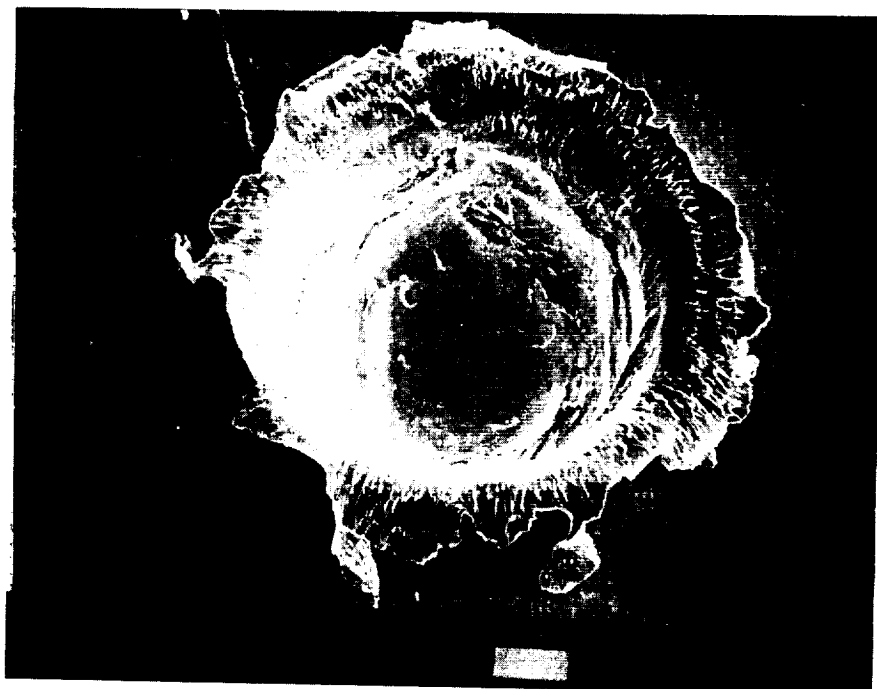


COMPONENT: EOO1
FEATURE: 211
CORE: LD-196
DIAMETER: 40 μ m
ORIGIN: Natural

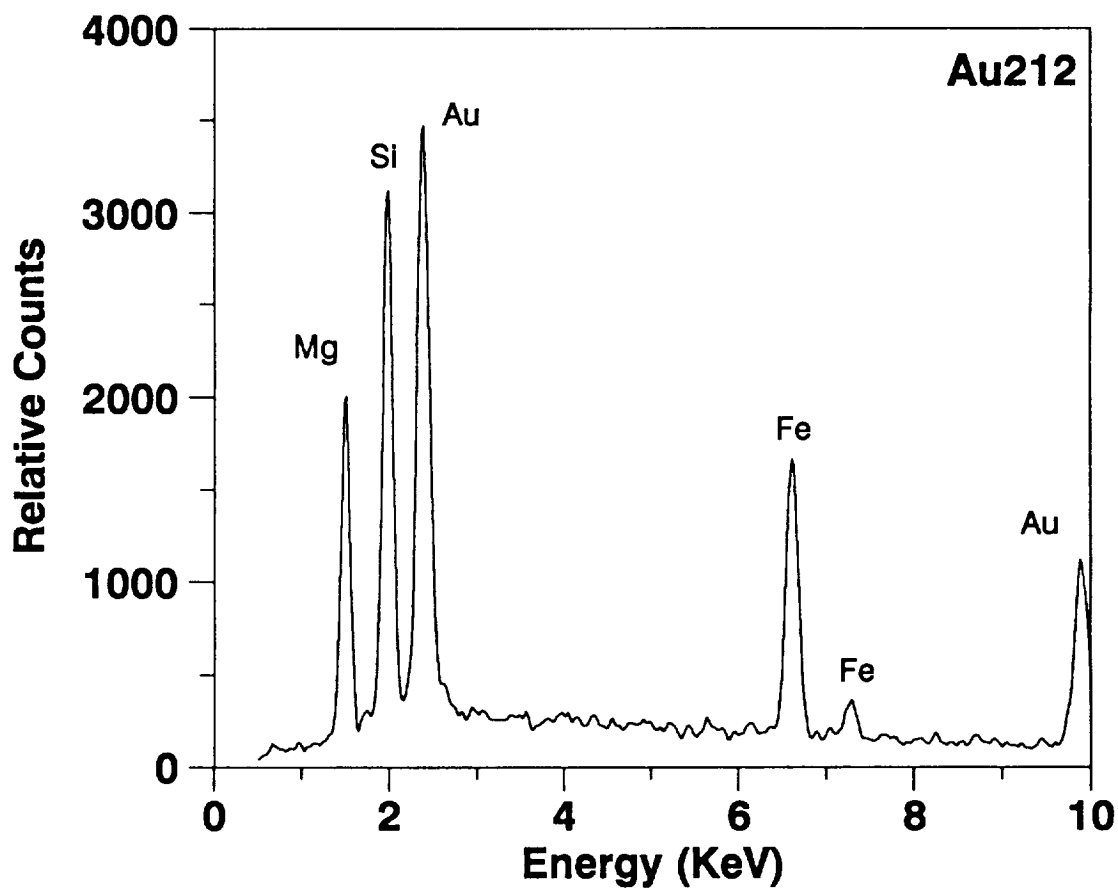


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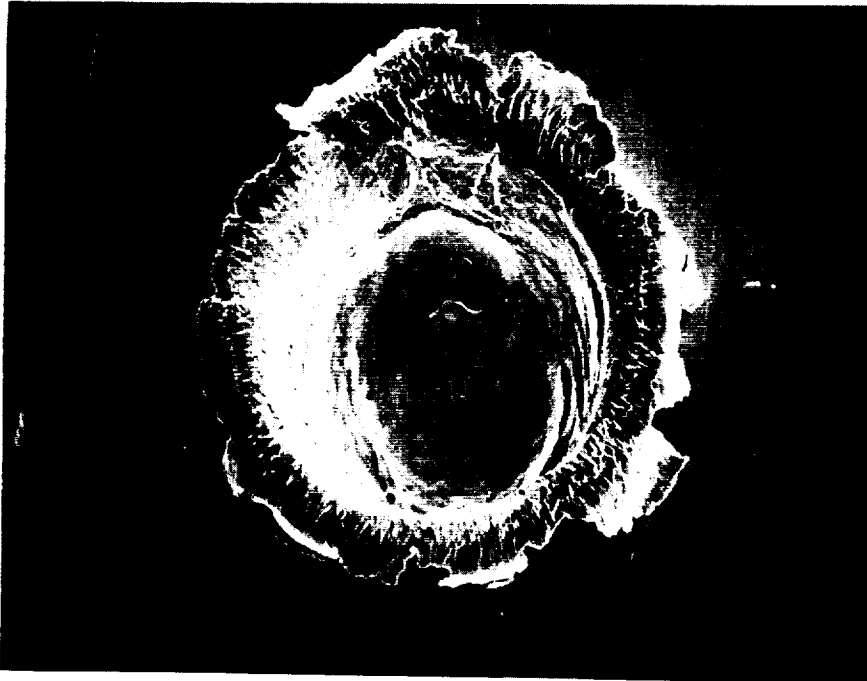


COMPONENT: E001
FEATURE: 212
CORE: LD-164
DIAMETER: 210 μ m
ORIGIN: Natural

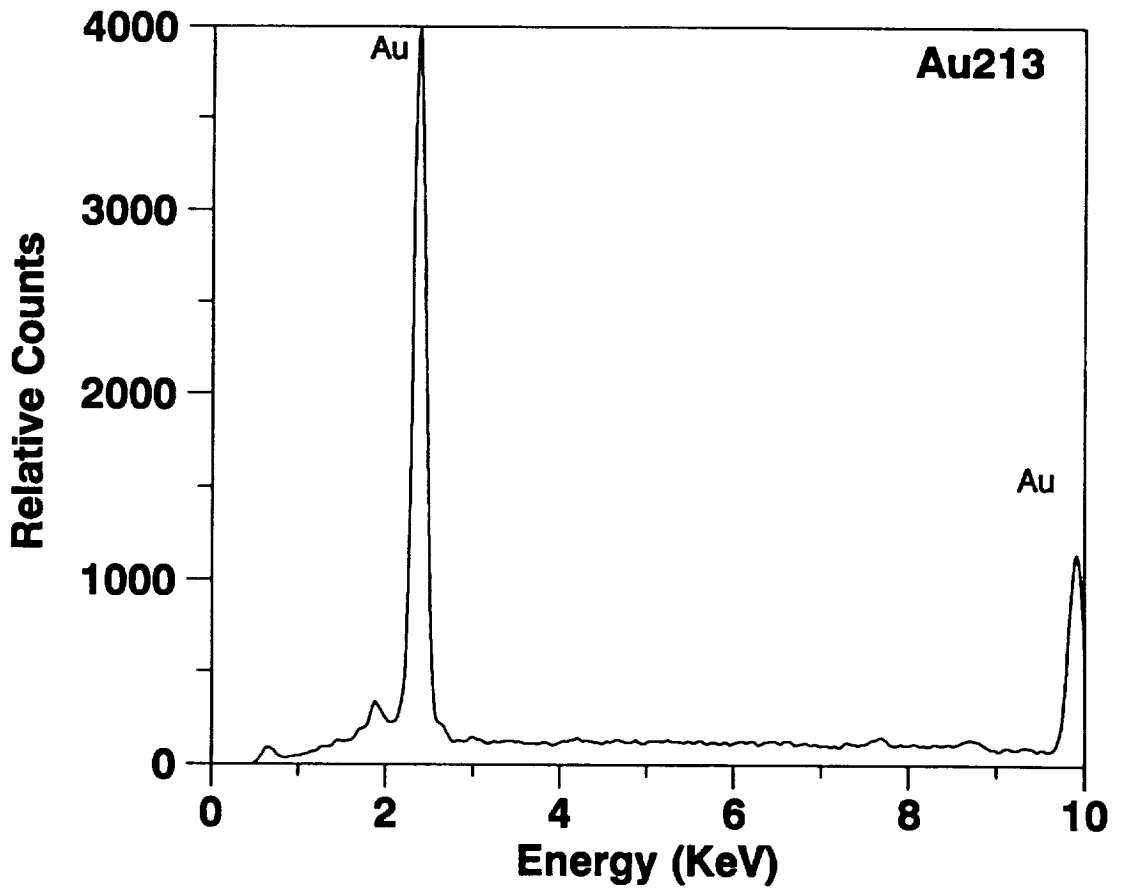


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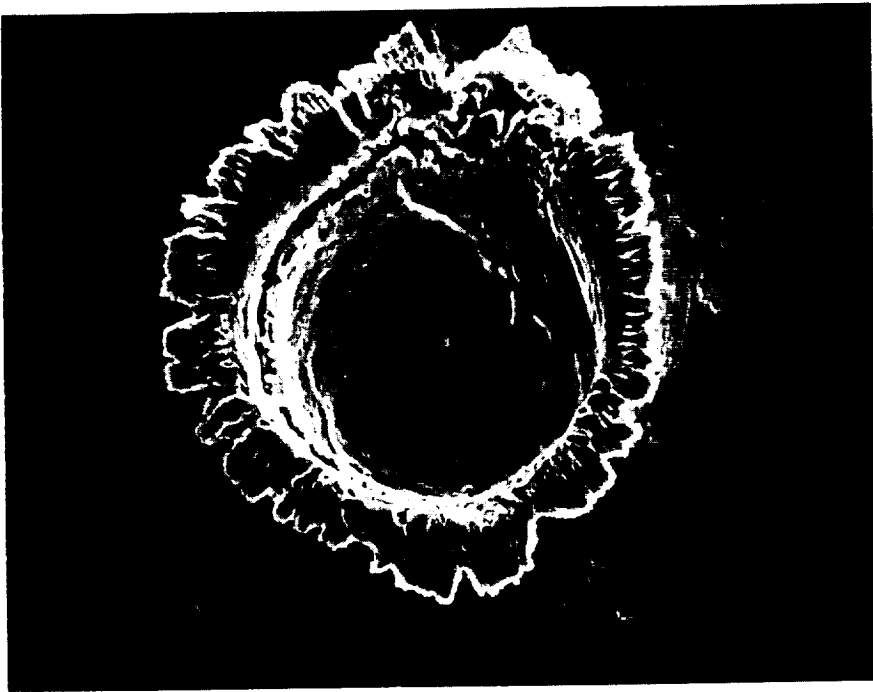


COMPONENT: E00I
FEATURE: 213
CORE: LD-167
DIAMETER: 145 μ m
ORIGIN: Unknown



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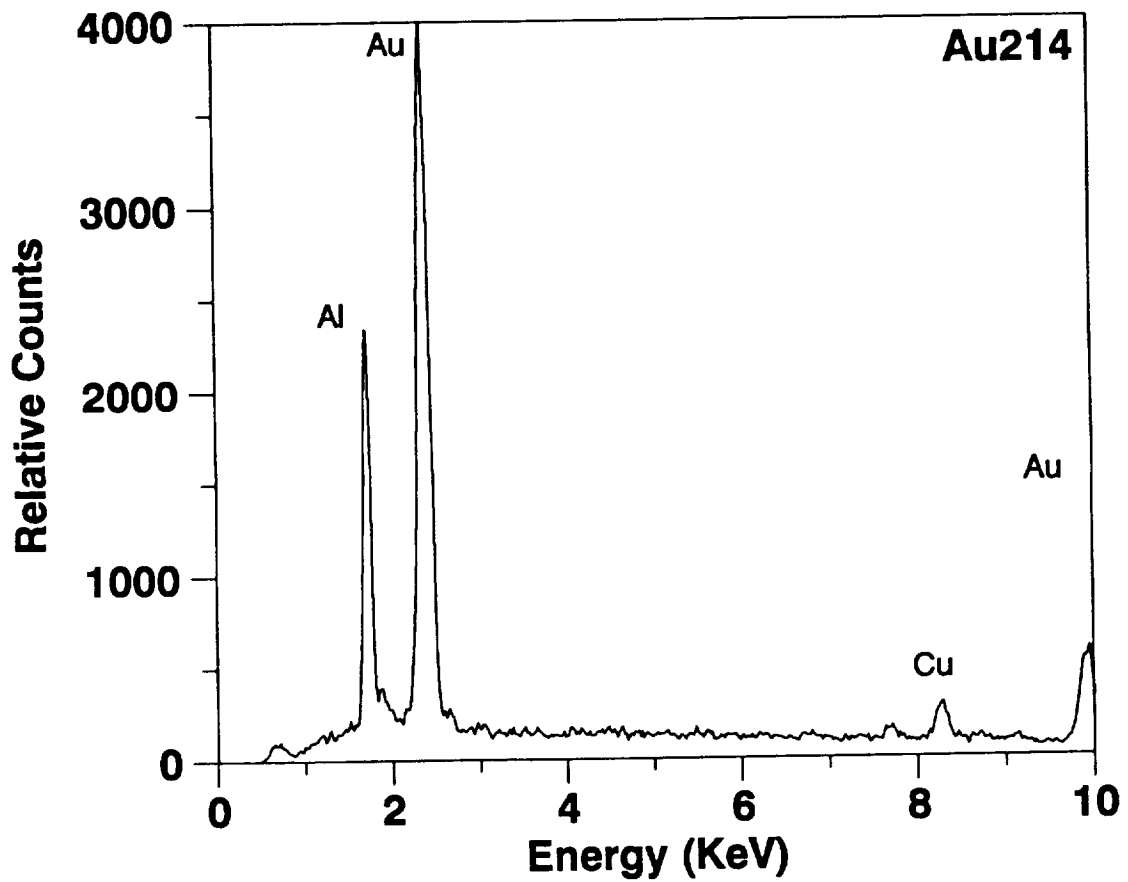
COMPONENT: EOOI

FEATURE: 214

CORE: LD-165

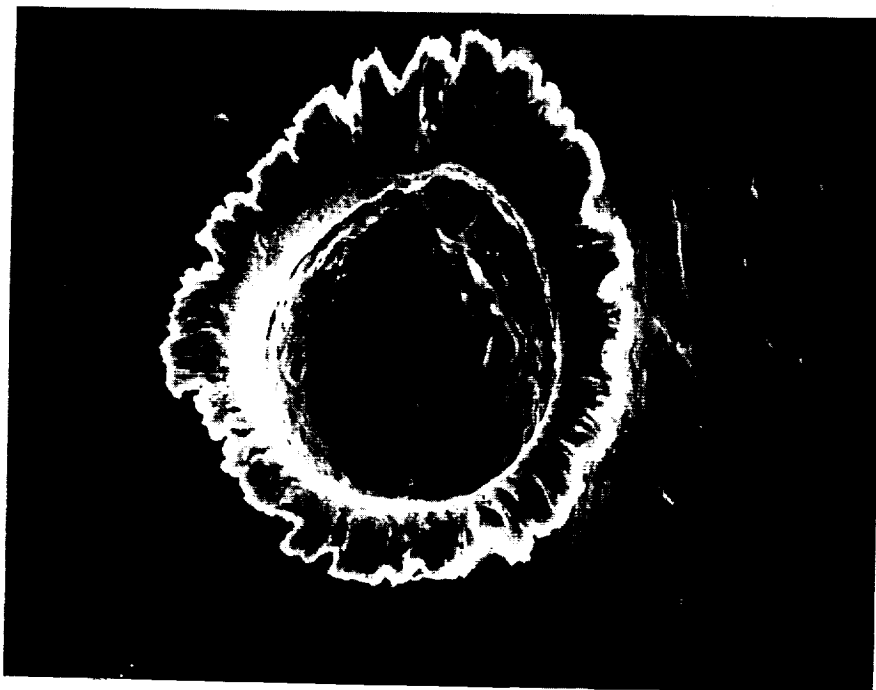
DIAMETER: 25 μ m

ORIGIN: Man-made

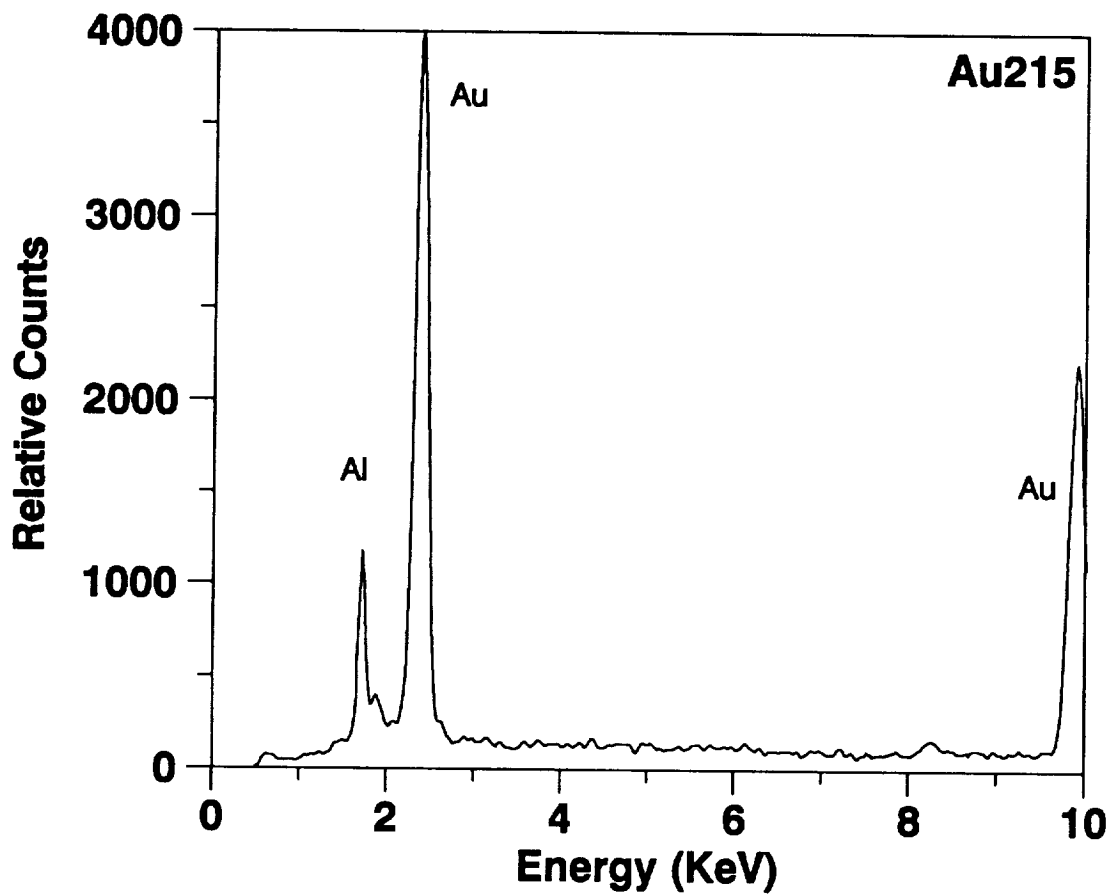


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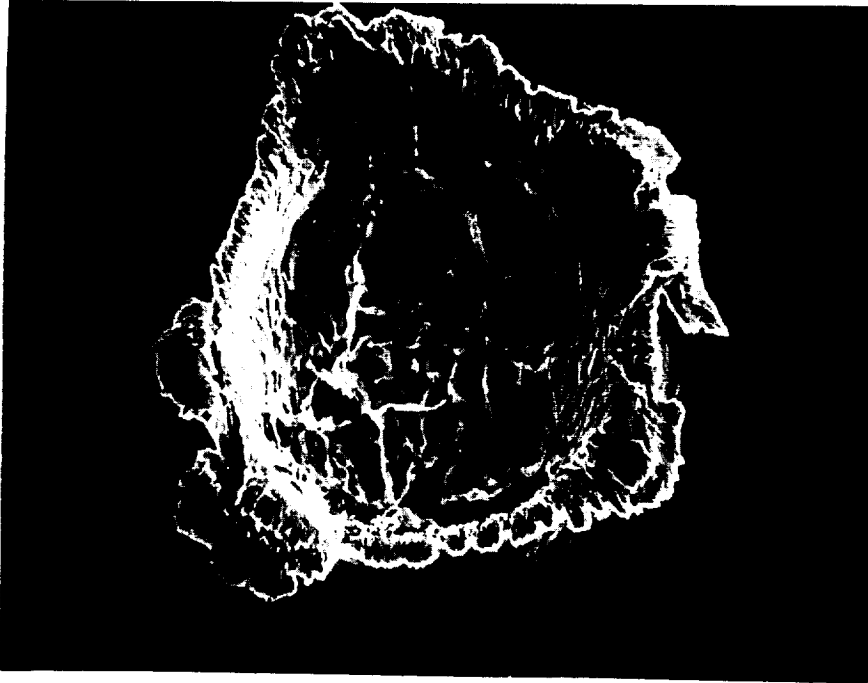


COMPONENT: EOOI
FEATURE: 215
CORE: LD-166
DIAMETER: 20 μ m
ORIGIN: Man-made

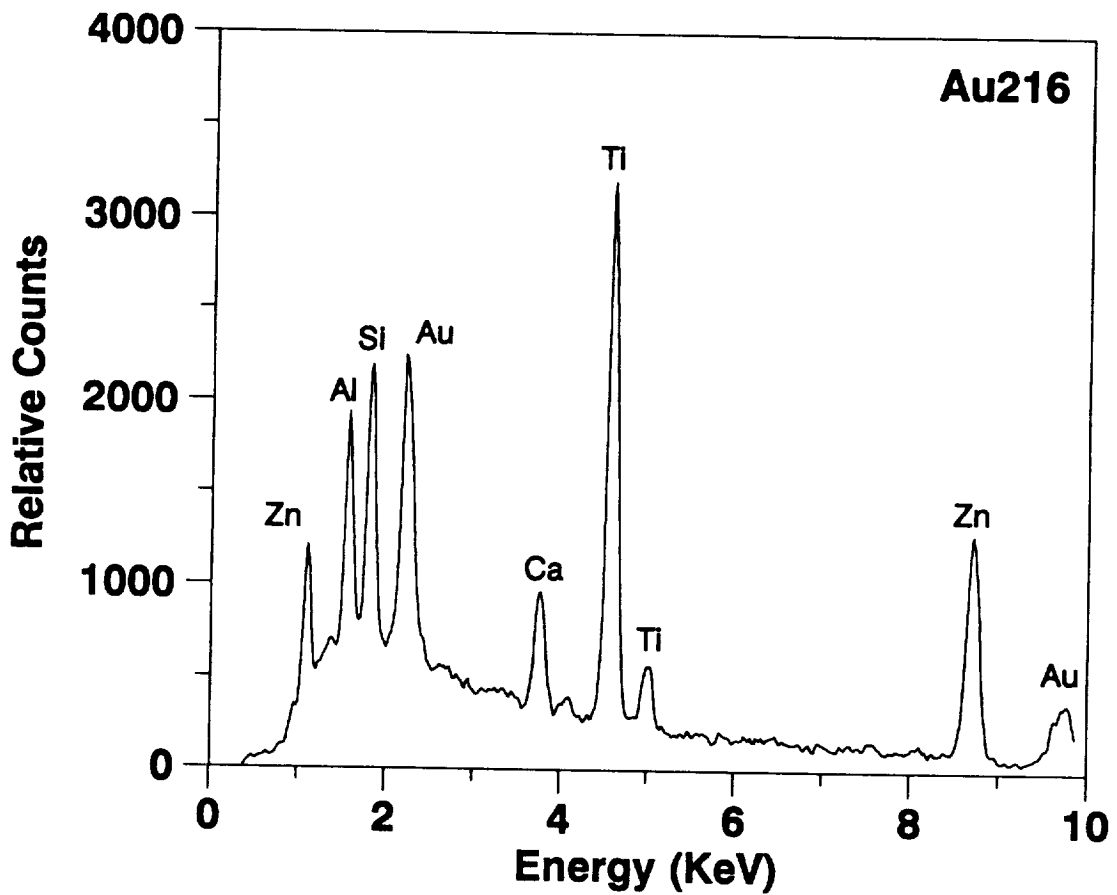


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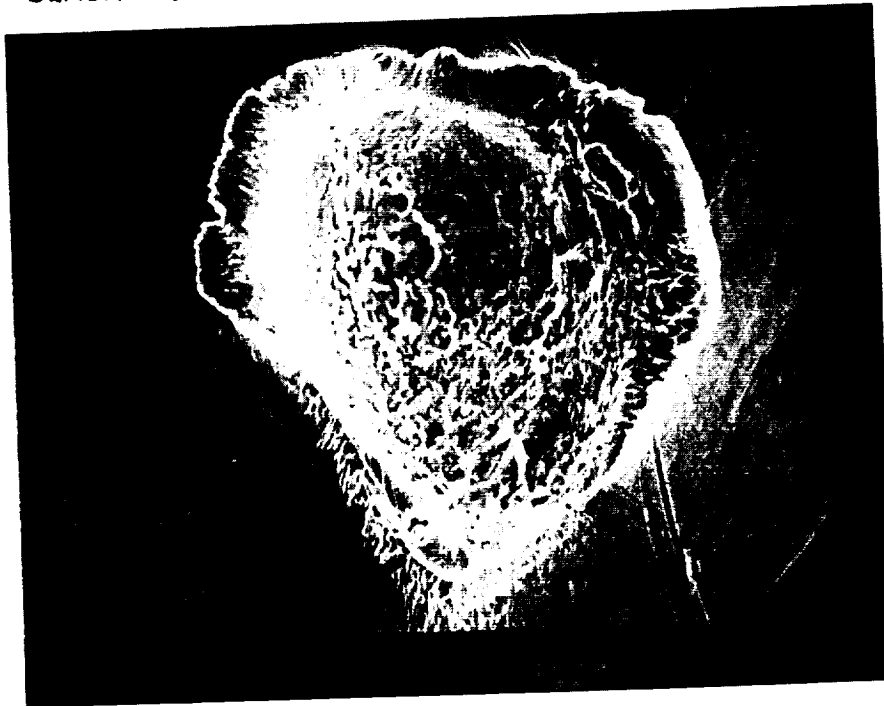


COMPONENT: EOOI
FEATURE: 216
CORE: LD-168
DIAMETER: 60 μm
ORIGIN: Man-made

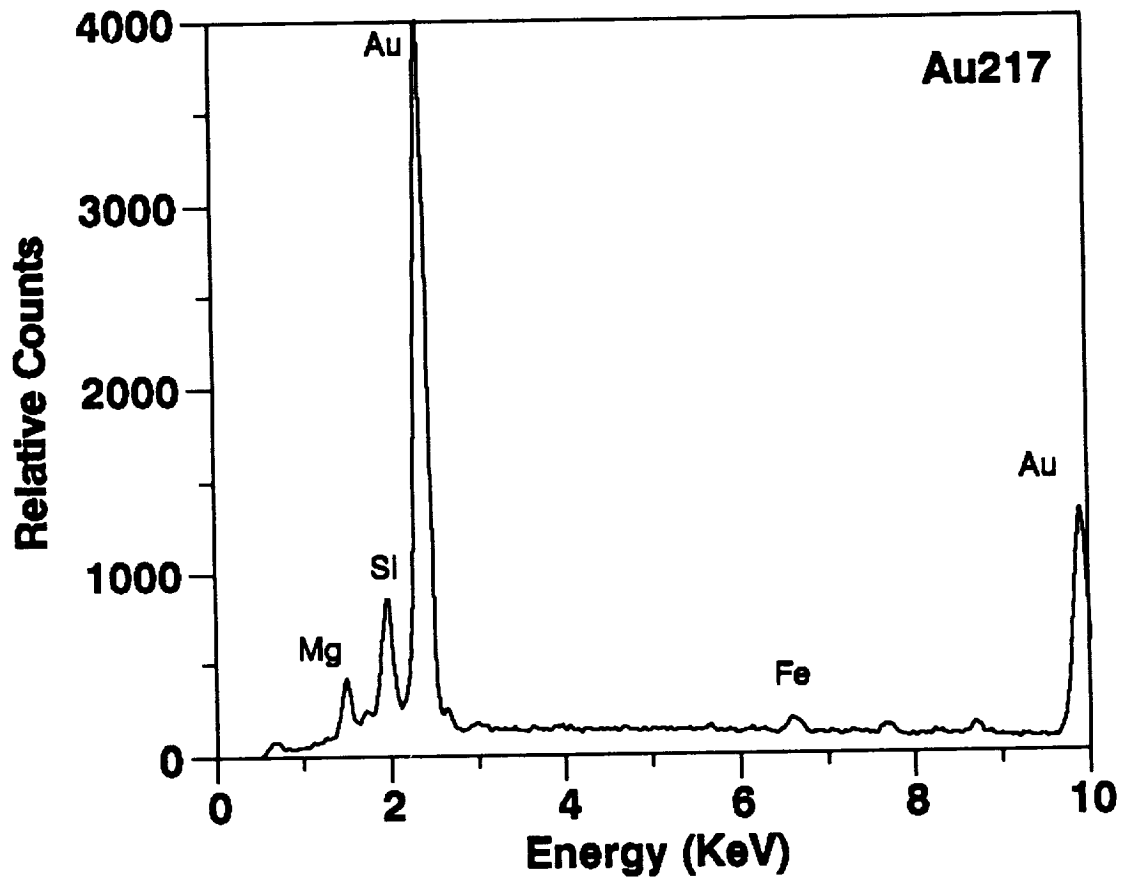


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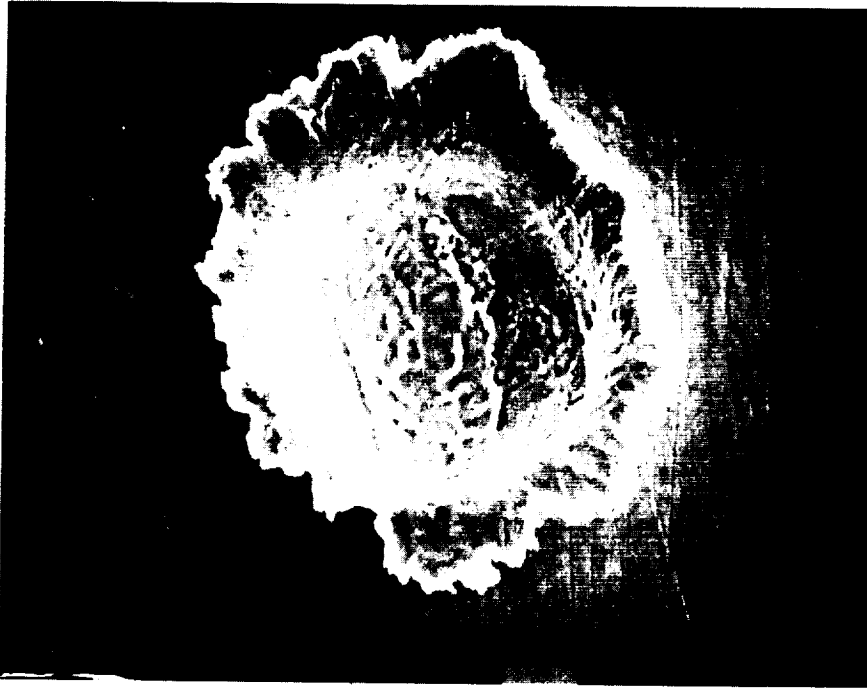


COMPONENT: E001
FEATURE: 217
CORE: LD-169
DIAMETER: 40 μ m
ORIGIN: Natural

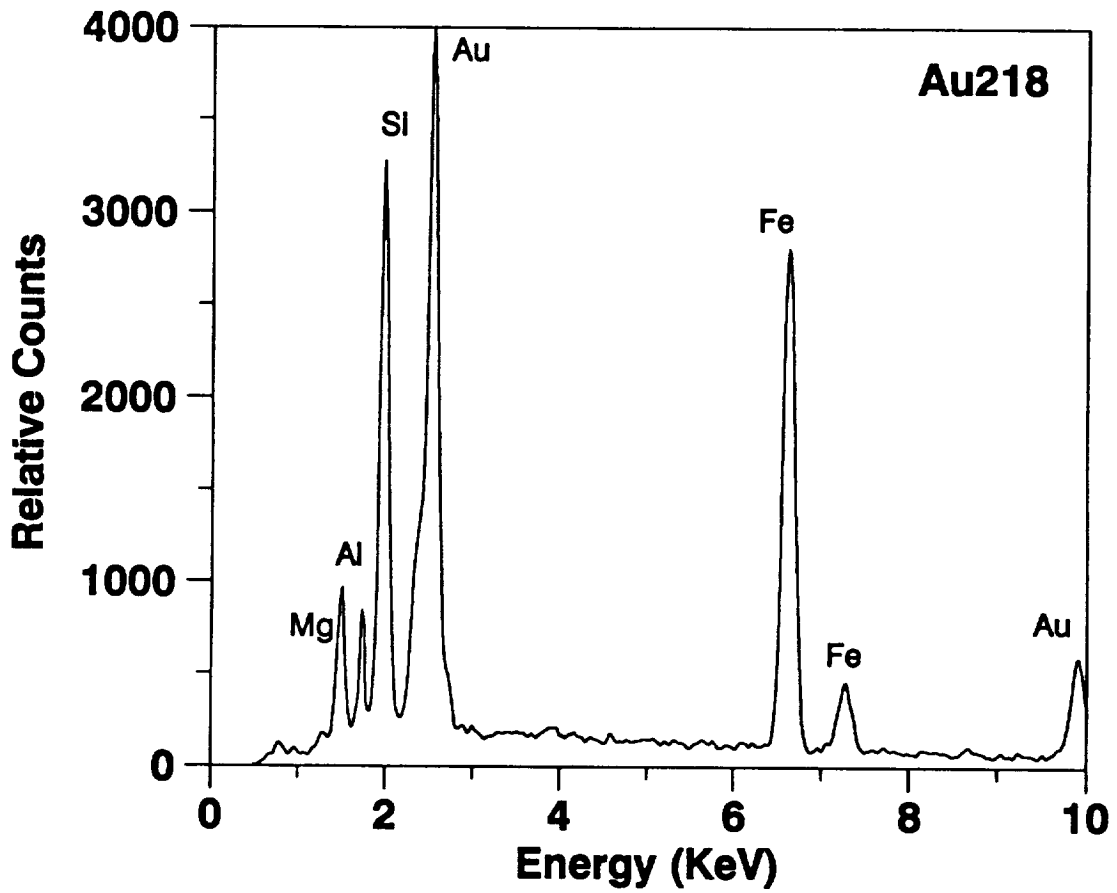


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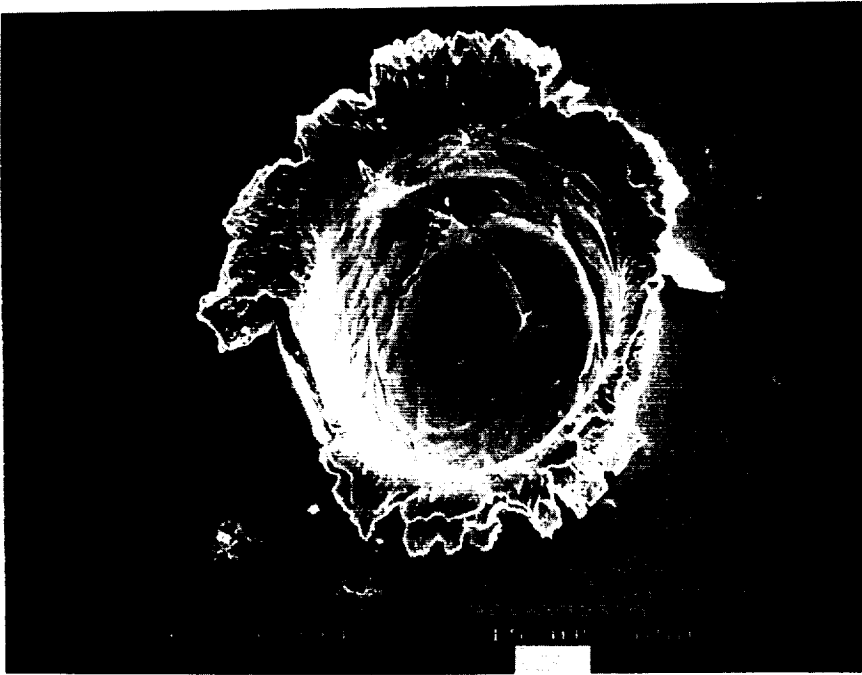


COMPONENT: EOOI
FEATURE: 218
CORE: LD-170
DIAMETER: 20 μ m
ORIGIN: Natural

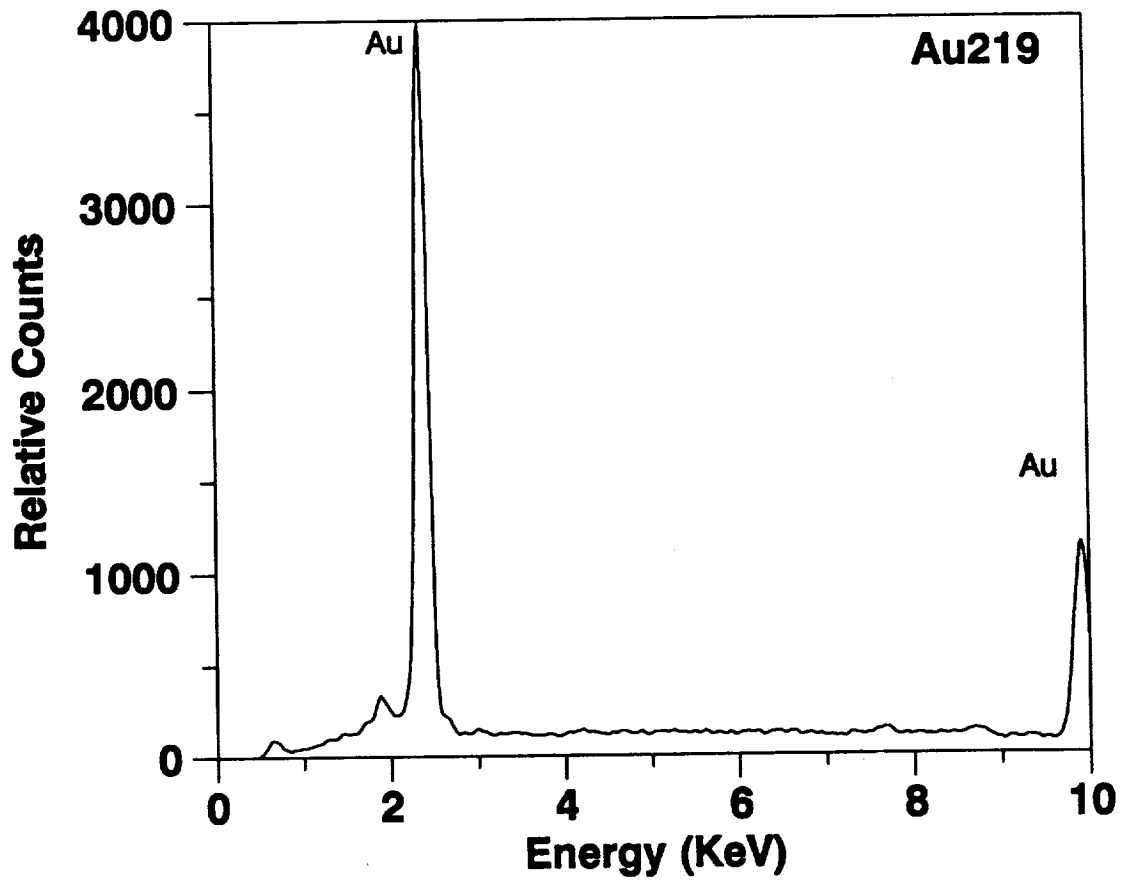


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COMPONENT: EOOI
FEATURE: 219
CORE: LD-195
DIAMETER: 70 μ m
ORIGIN: Unknown

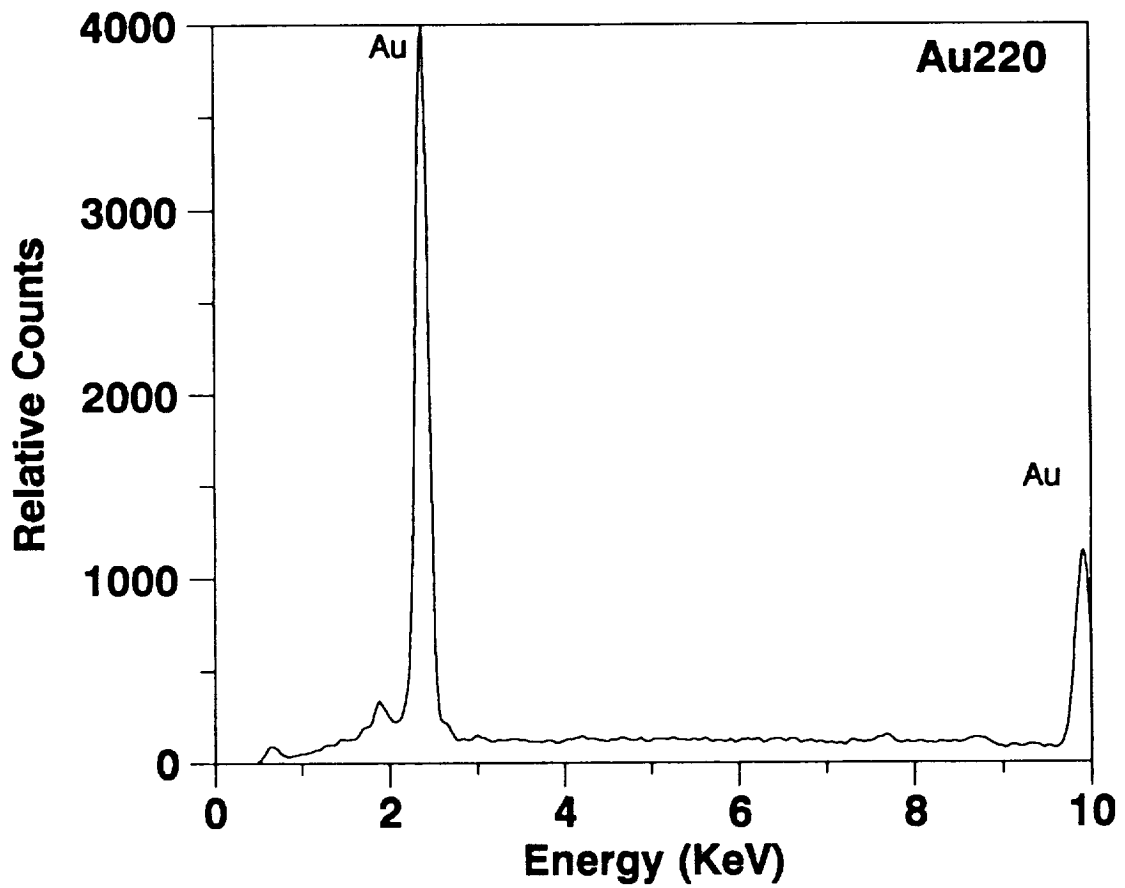


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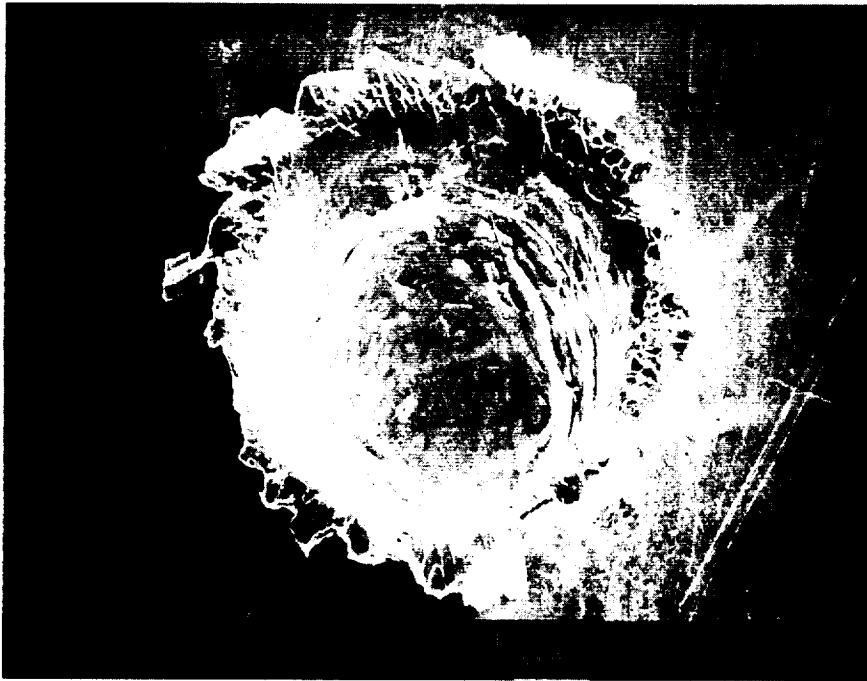


COMPONENT: EOOI
FEATURE: 220
CORE: LD-189
DIAMETER: 25 μ m
ORIGIN: Unknown

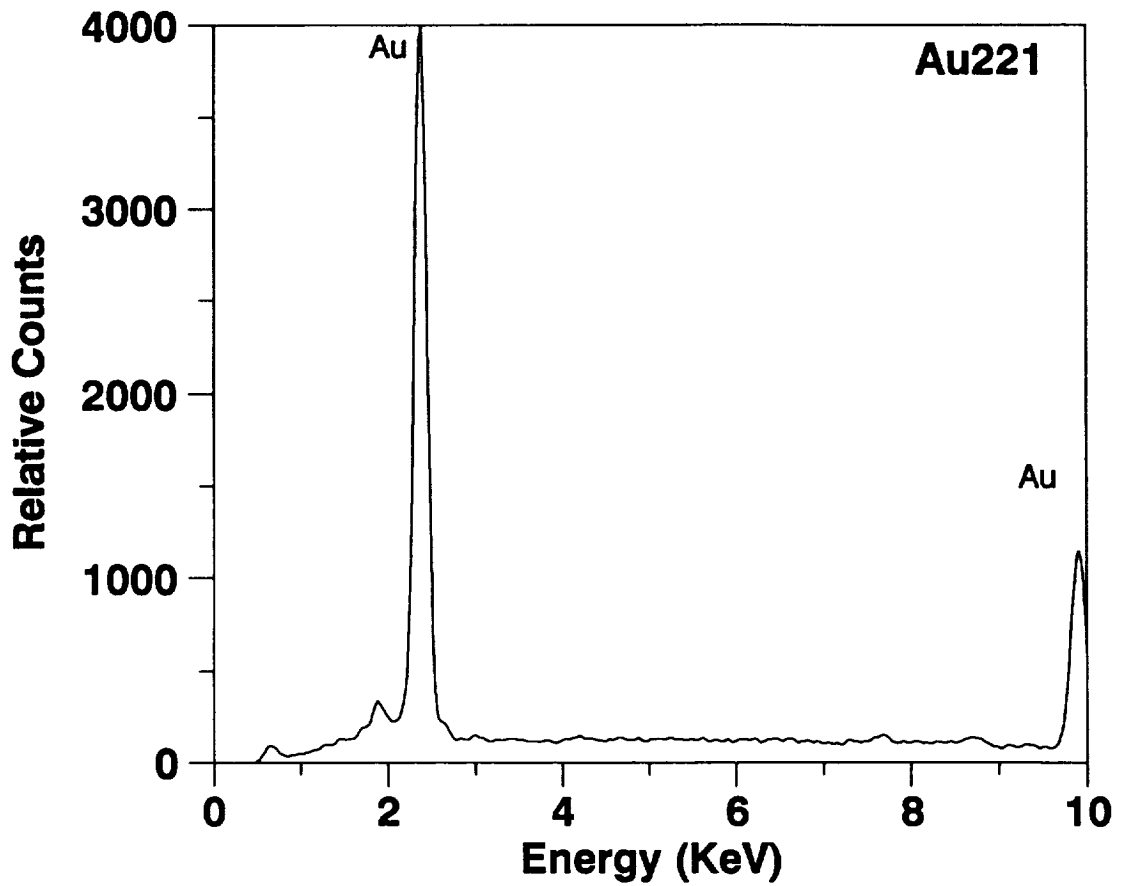


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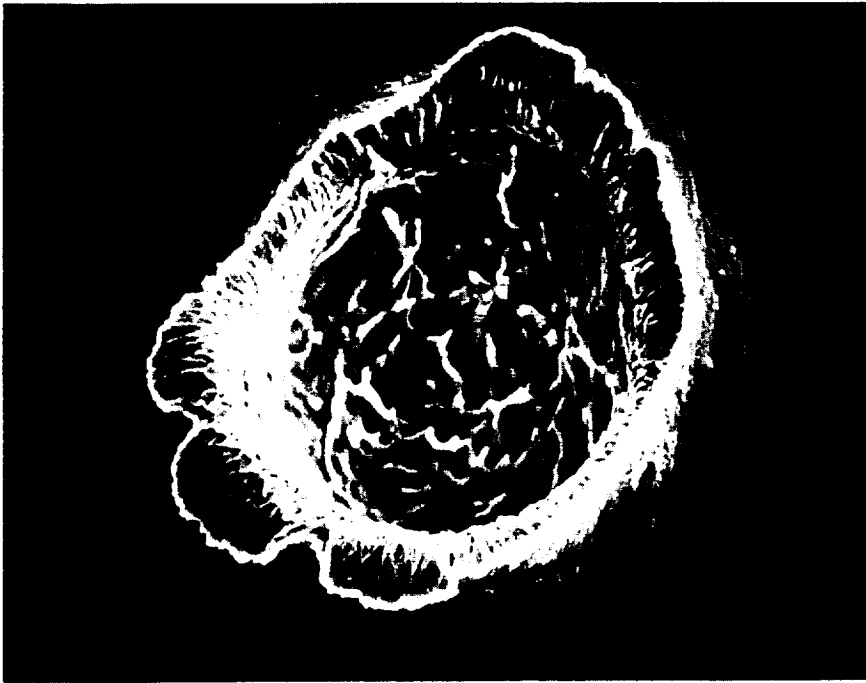


COMPONENT: E001
FEATURE: 221
CORE: LD-191
DIAMETER: 100 μ m
ORIGIN: Unknown

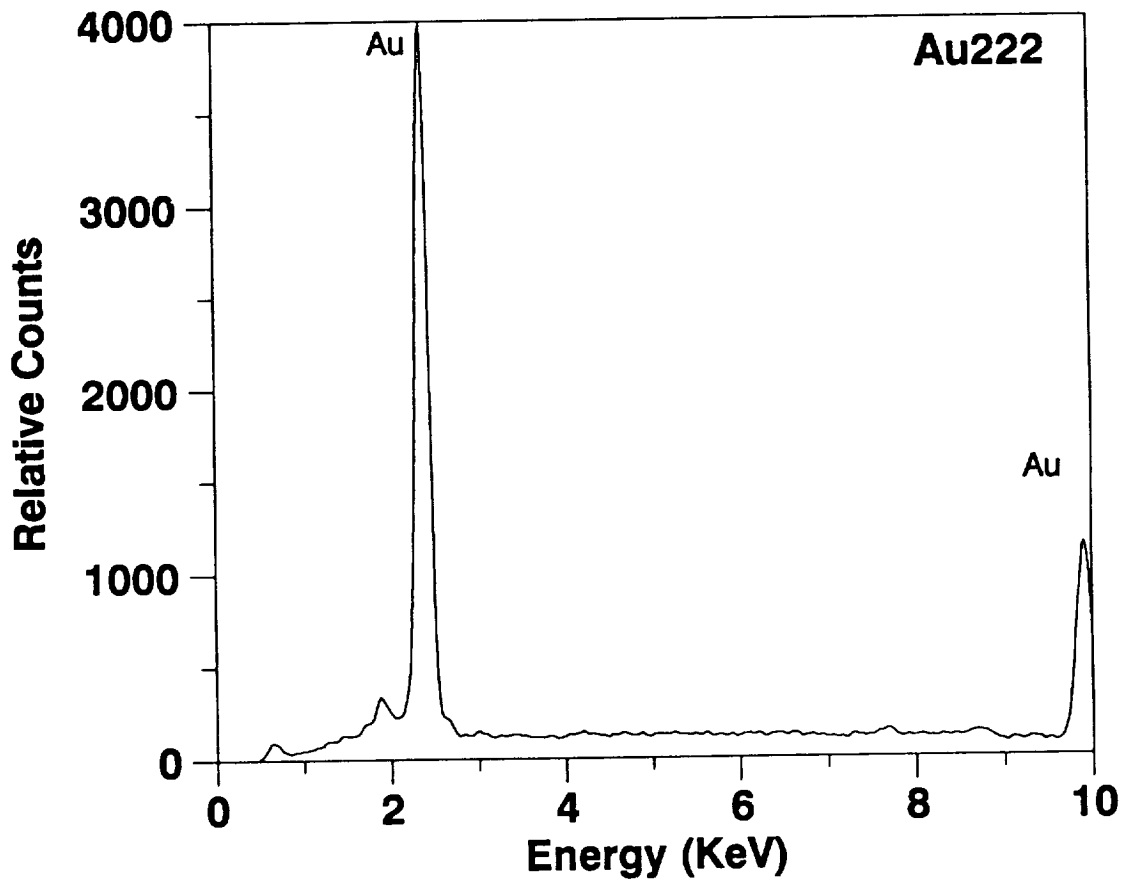


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COMPONENT: E00I
FEATURE: 222
CORE: LD-192
DIAMETER: 25 μ m
ORIGIN: Unknown

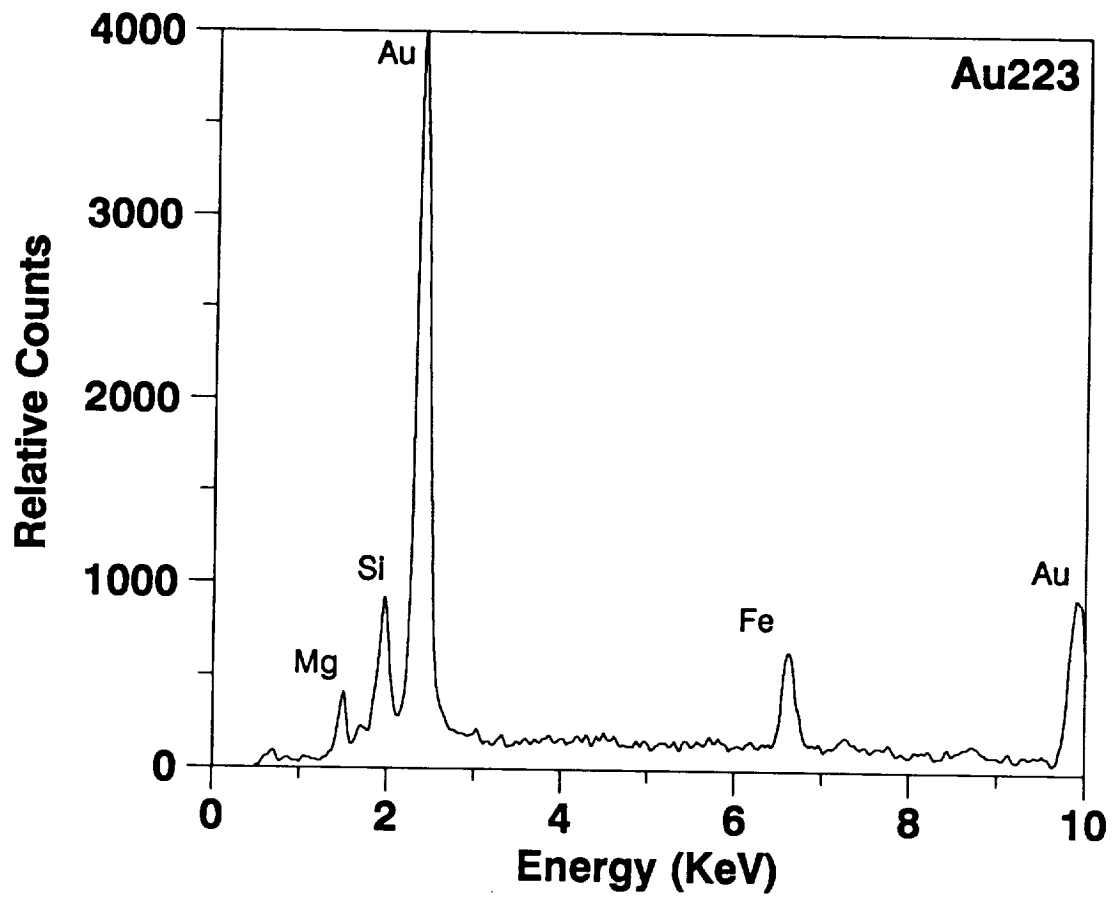


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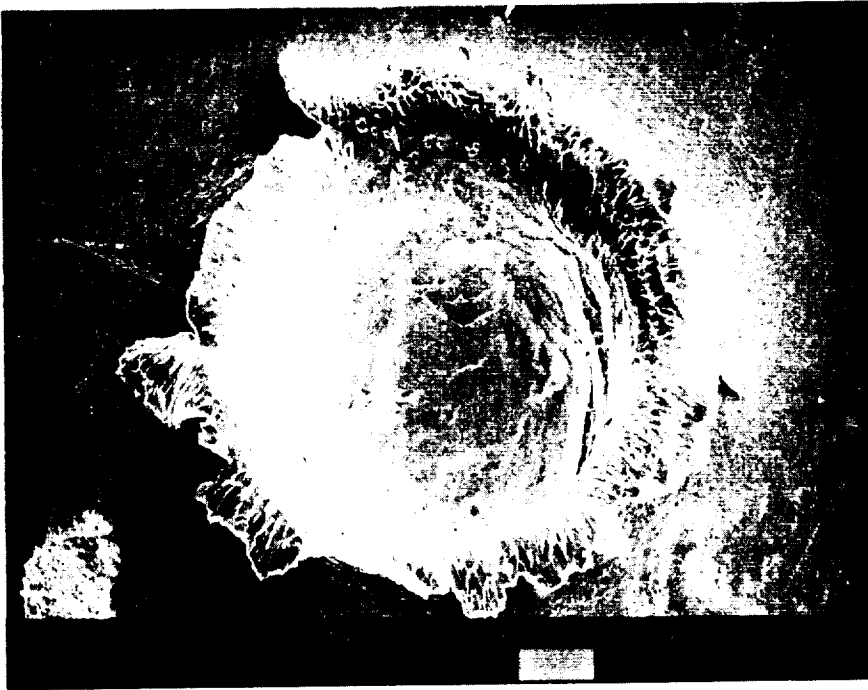


COMPONENT: E001
FEATURE: 223
CORE: LD-193
DIAMETER: 45 μm
ORIGIN: Natural

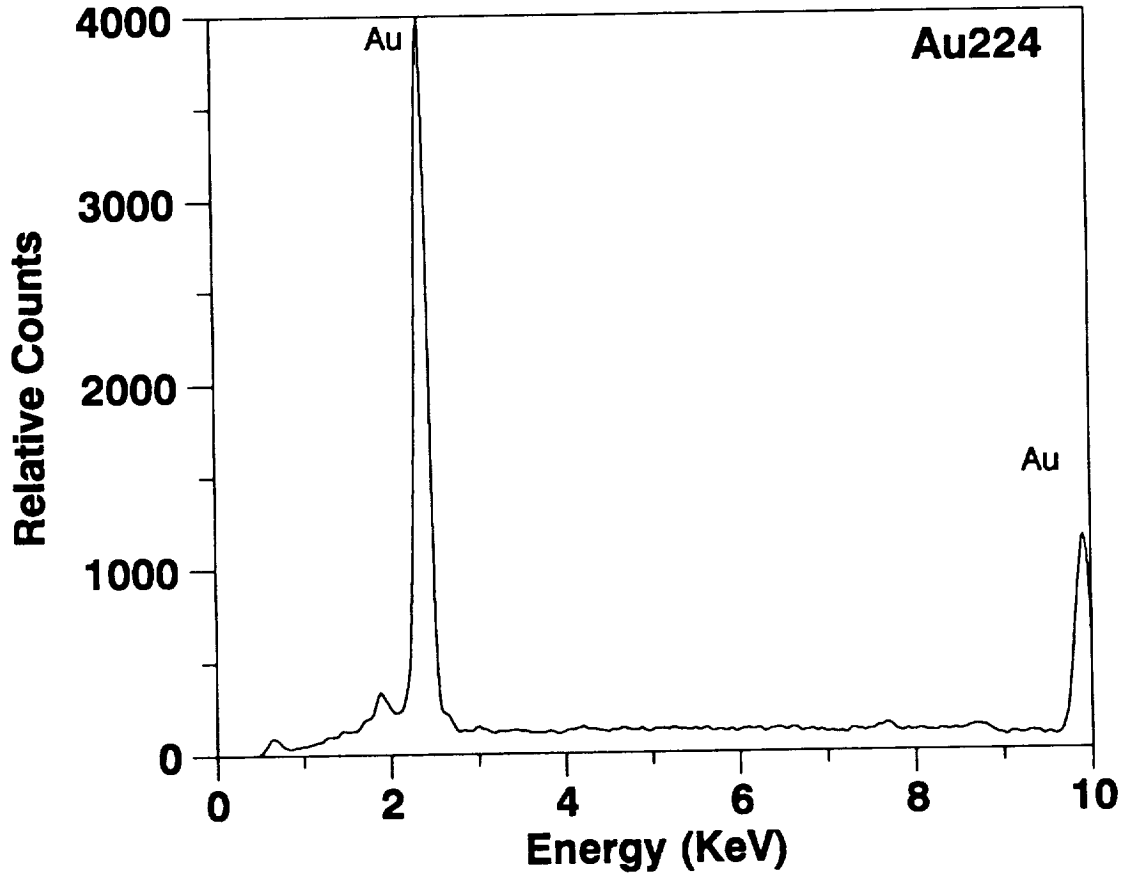


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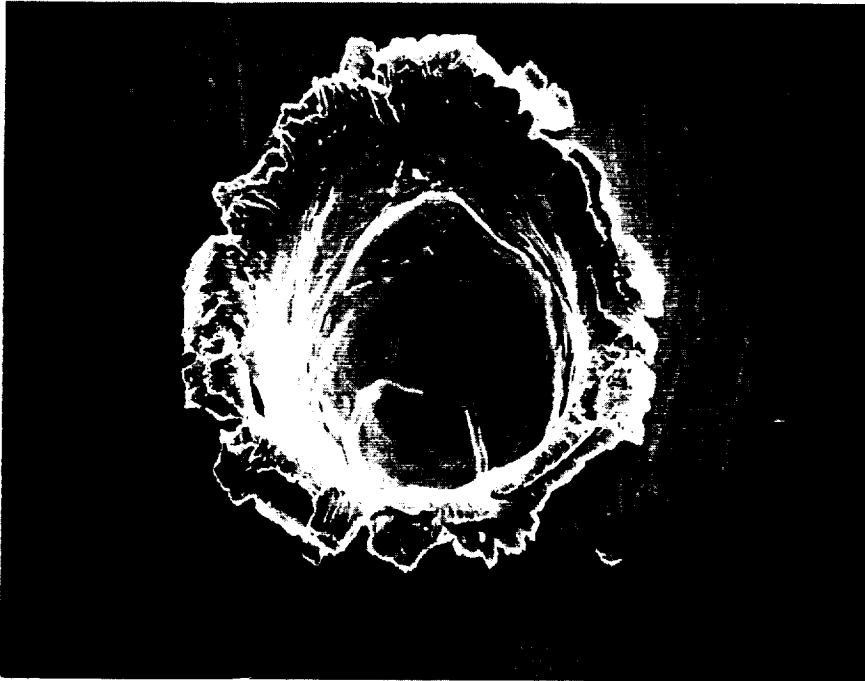


COMPONENT: EOOI
FEATURE: 224
CORE: LD-188
DIAMETER: 180 μ m
ORIGIN: Unknown



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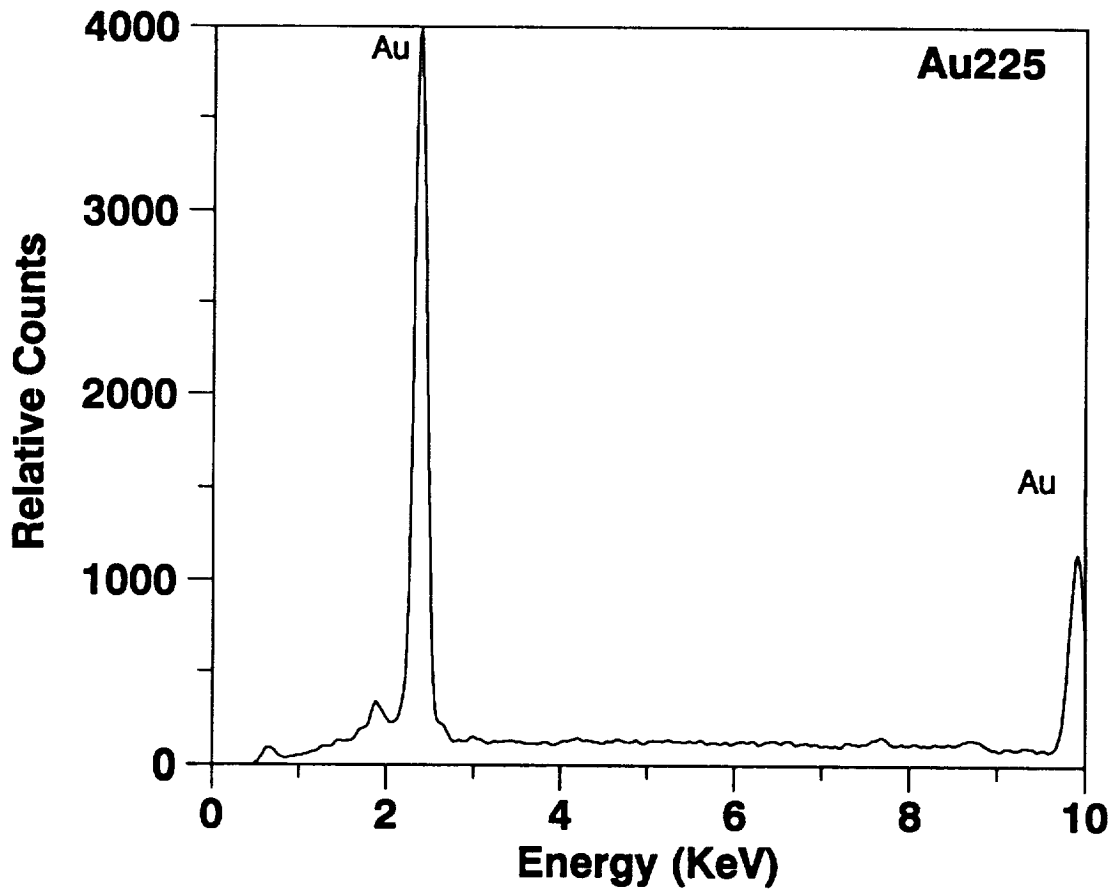
COMPONENT: E00I

FEATURE: 225

CORE: LD-194

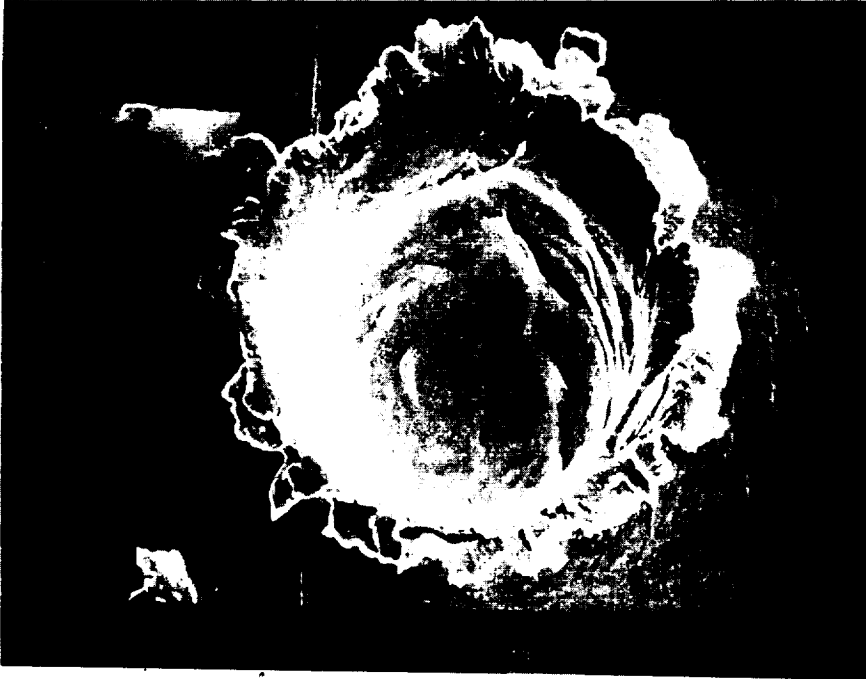
DIAMETER: 80 μm

ORIGIN: Unknown



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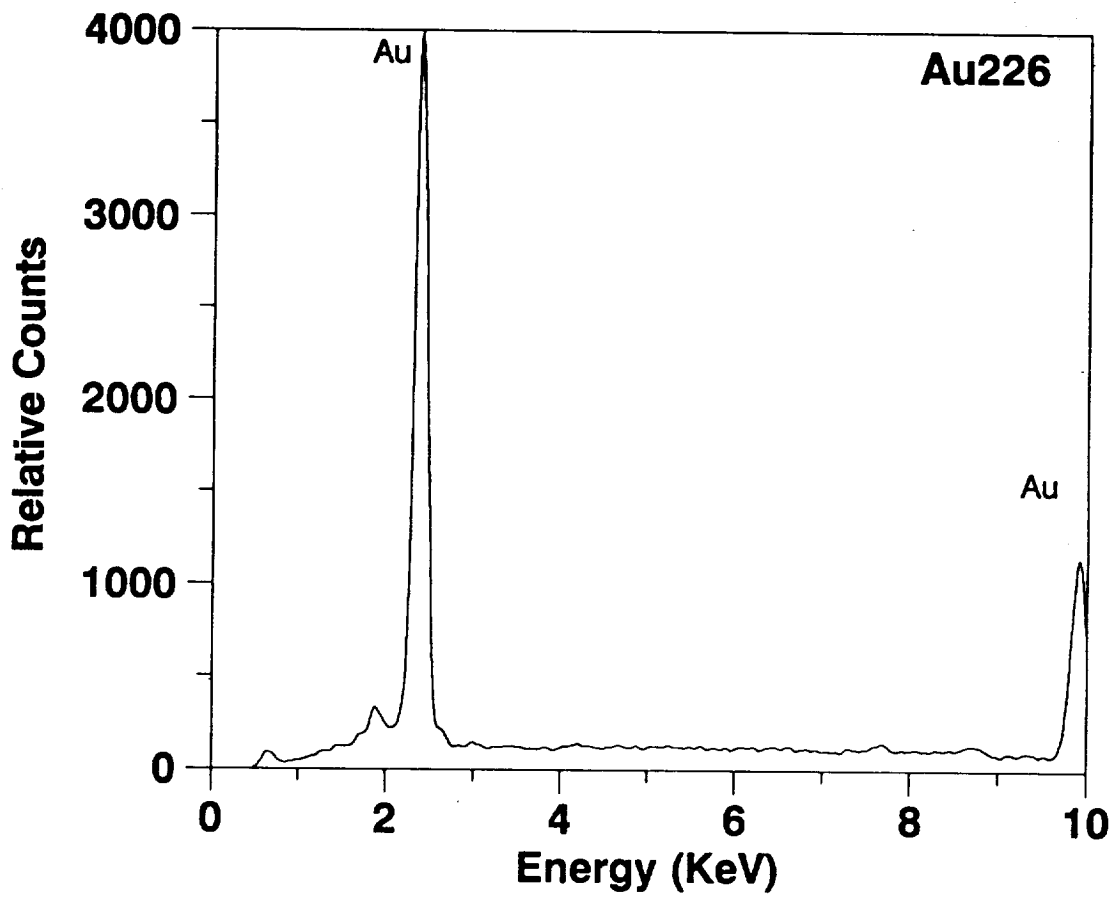
COMPONENT: EOOI

FEATURE: 226

CORE: LD-190

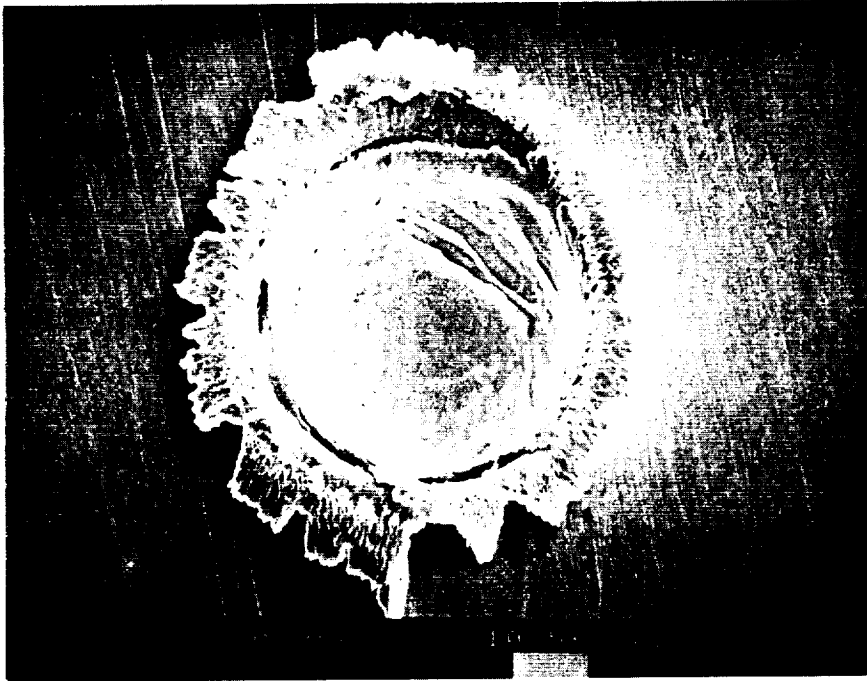
DIAMETER: 60 μm

ORIGIN: Unknown

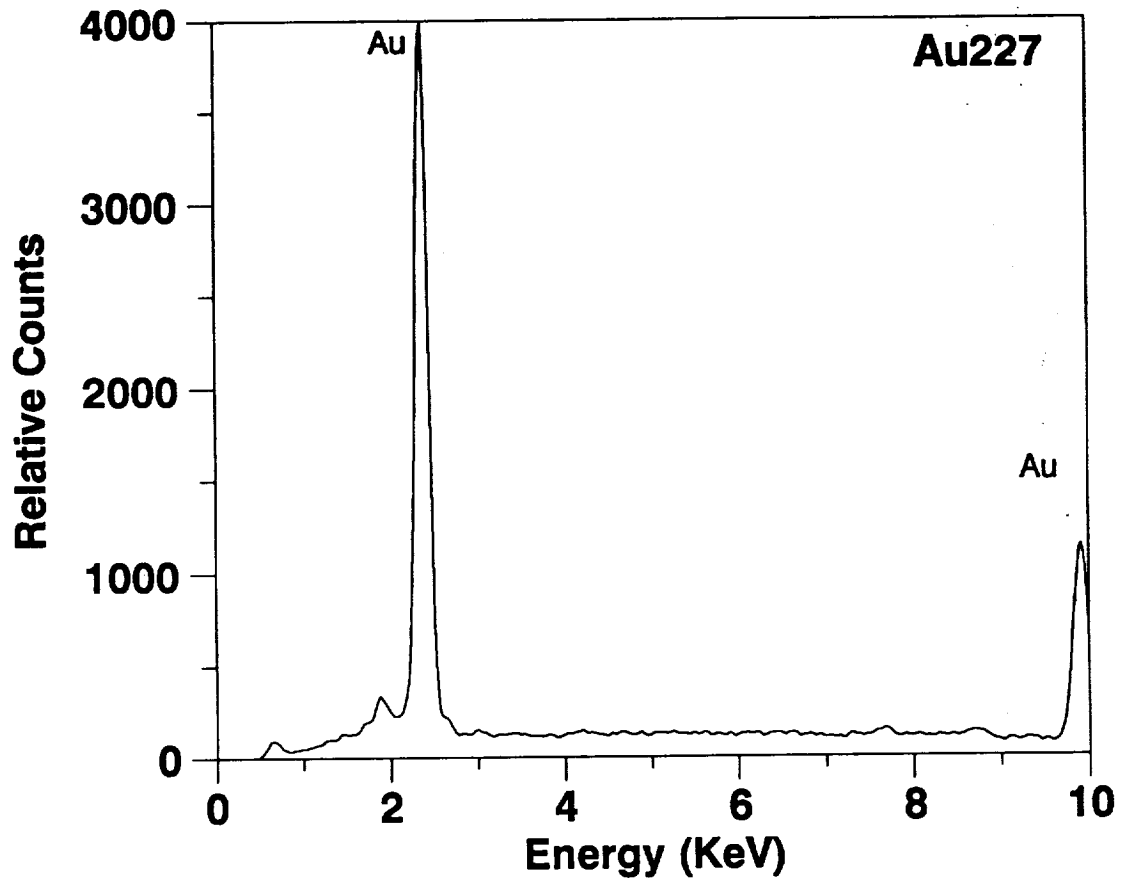


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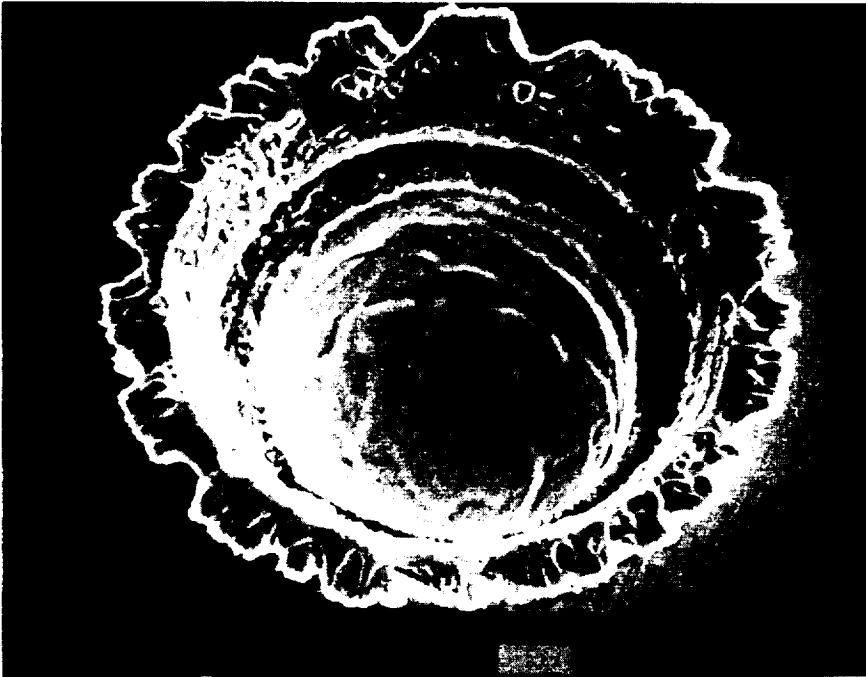


COMPONENT: E001
FEATURE: 227
CORE: LD-171
DIAMETER: 50 μ m
ORIGIN: Unknown



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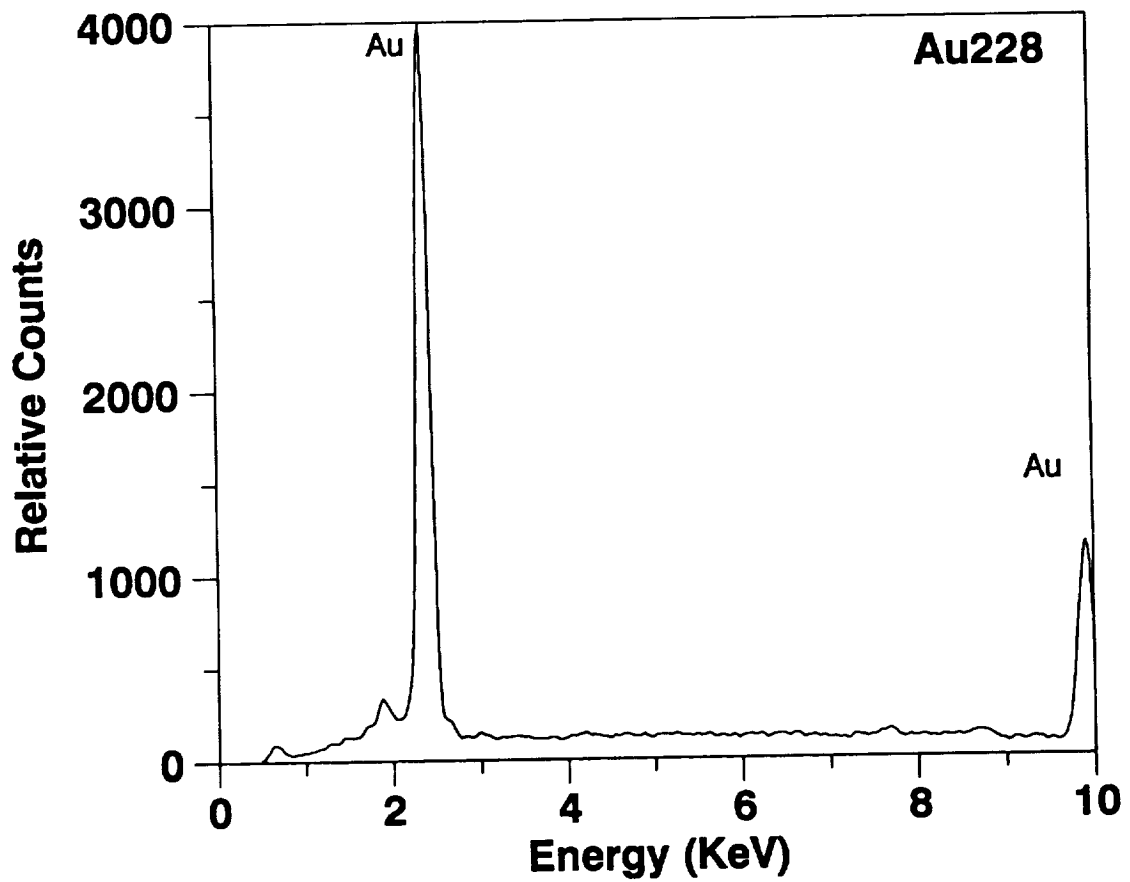
COMPONENT: EOOI

FEATURE: 228

CORE: LD-178

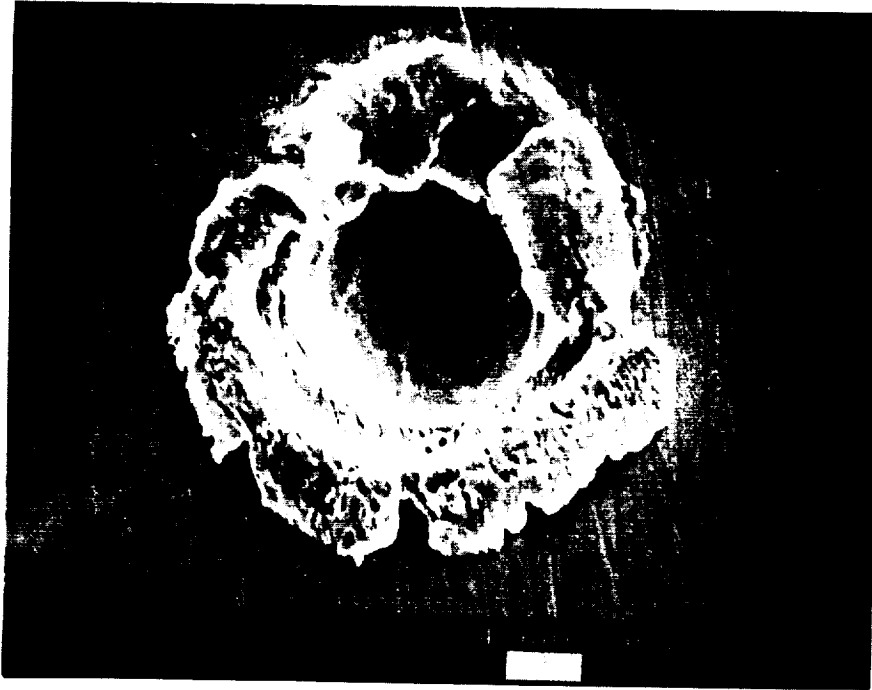
DIAMETER: 50 μ m

ORIGIN: Unknown

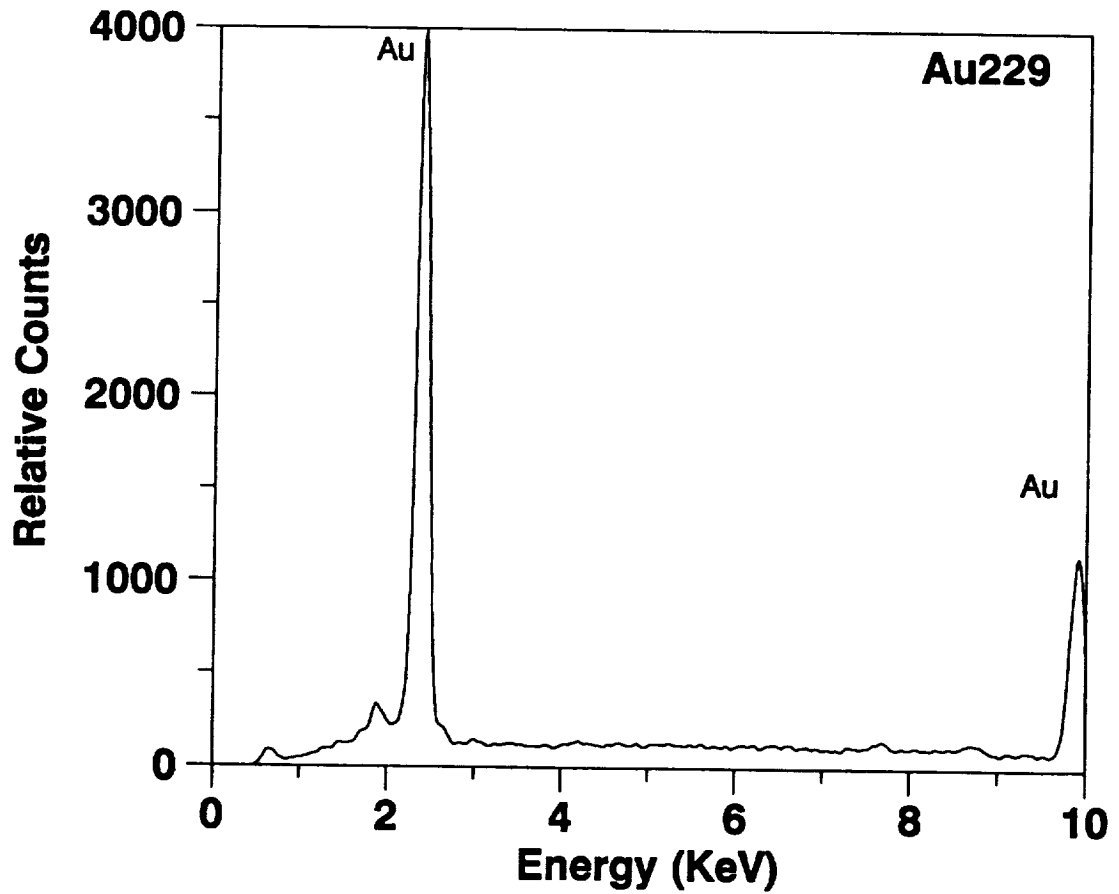


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COMPONENT: E00I
FEATURE: 229
CORE: LD-179
DIAMETER: 15 μ m
ORIGIN: Unknown

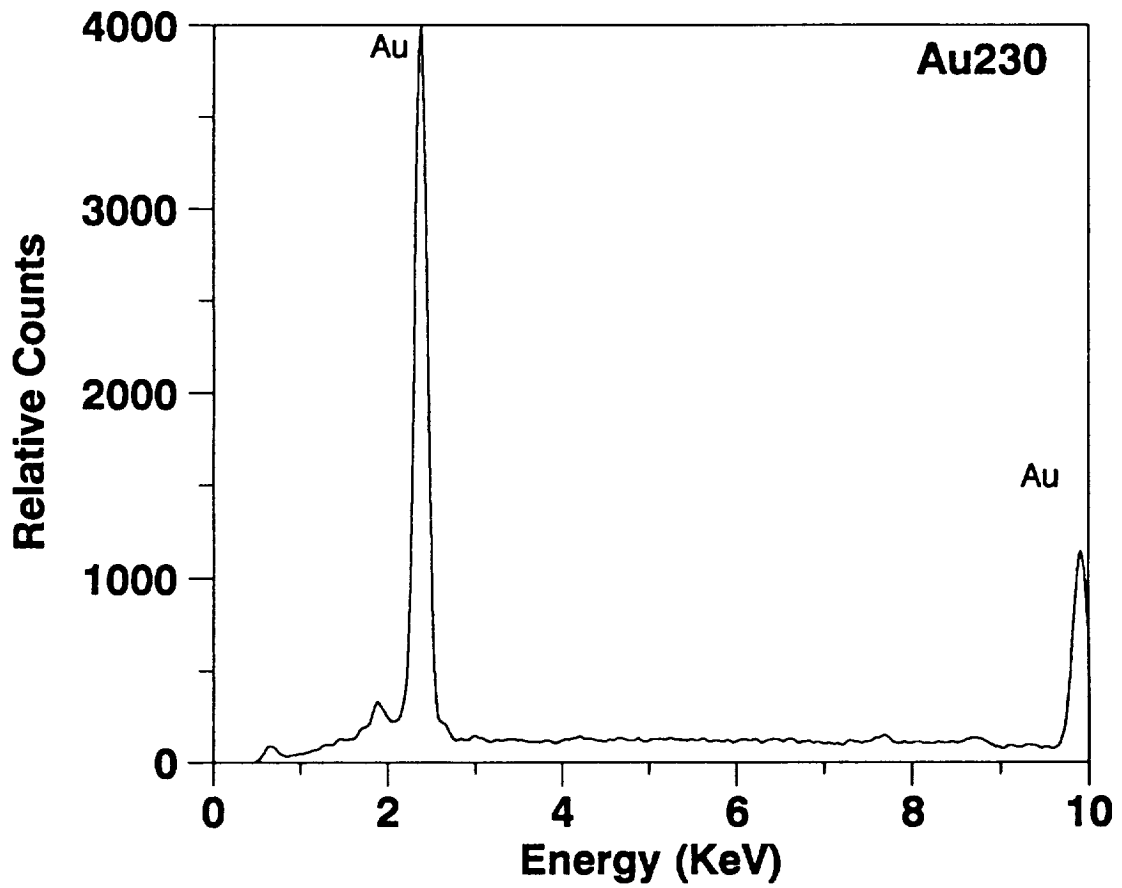


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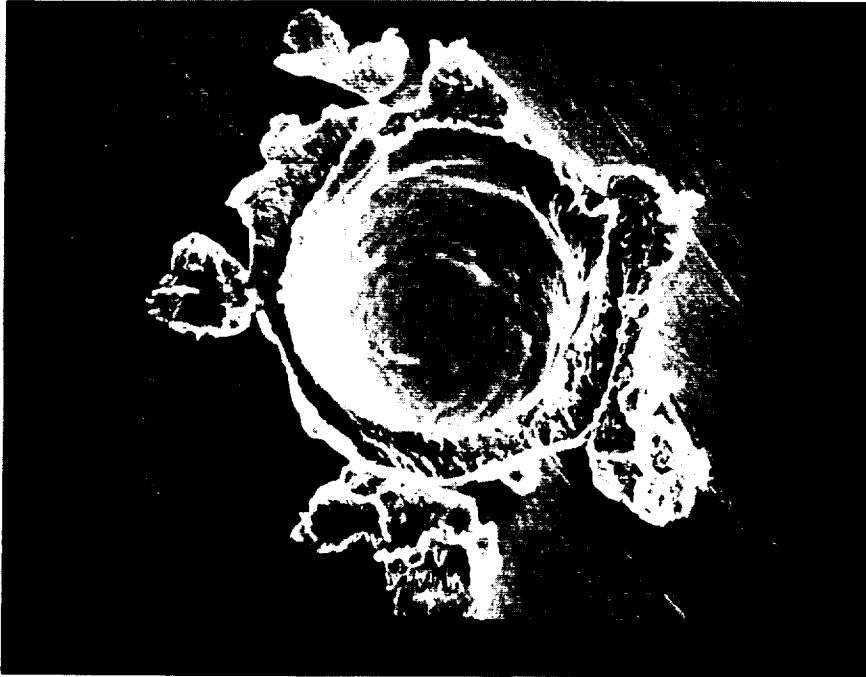


COMPONENT: EOOI
FEATURE: 230
CORE: LD-172
DIAMETER: 20 μm
ORIGIN: Unknown

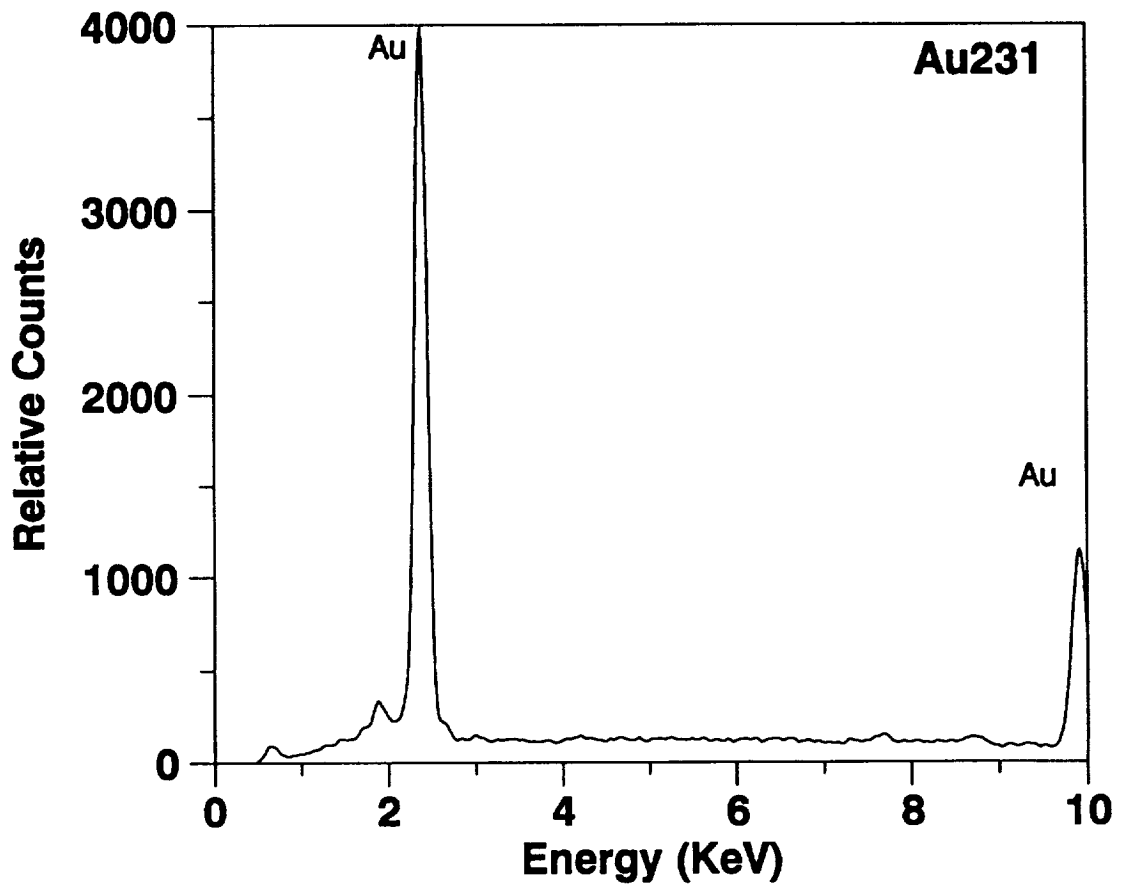


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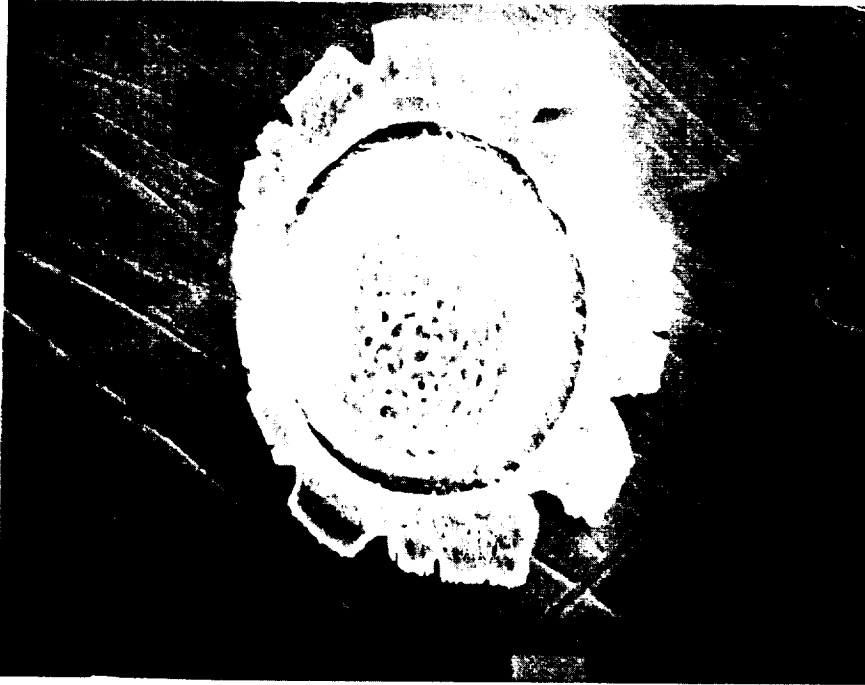


COMPONENT: EOOI
FEATURE: 231
CORE: LD-181
DIAMETER: 20 μ m
ORIGIN: Unknown

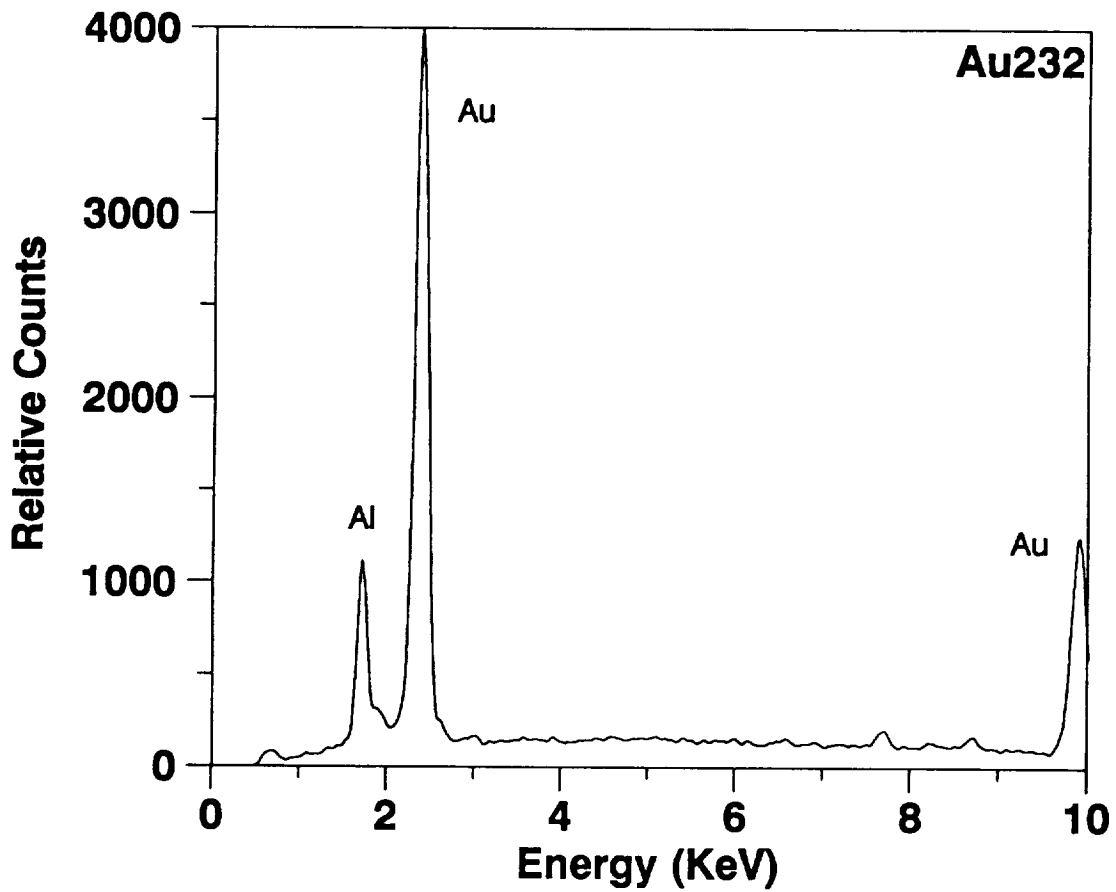


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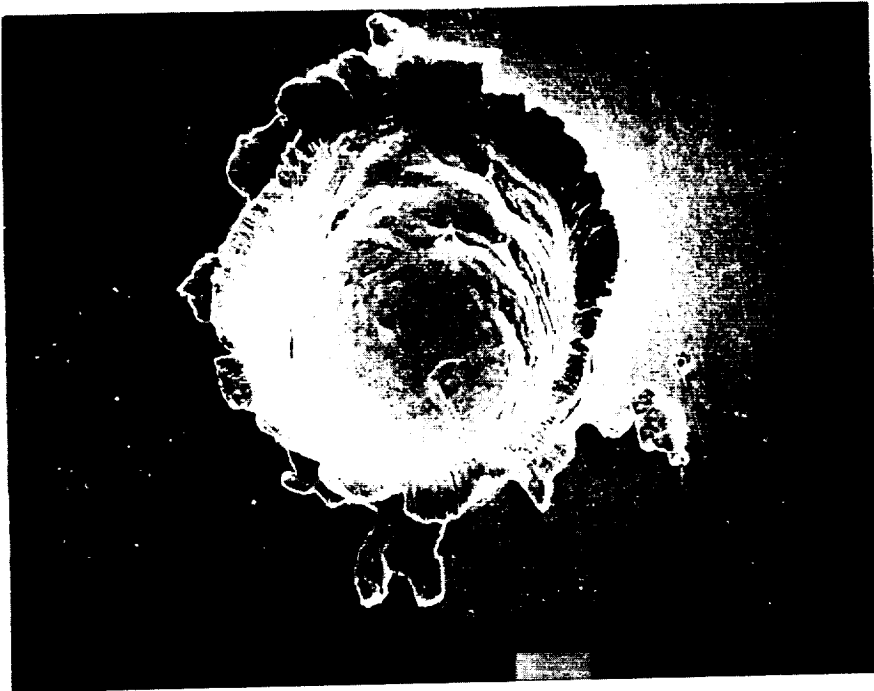


COMPONENT: EOOI
FEATURE: 232
CORE: LD-181
DIAMETER: 20 μ m
ORIGIN: Man-made

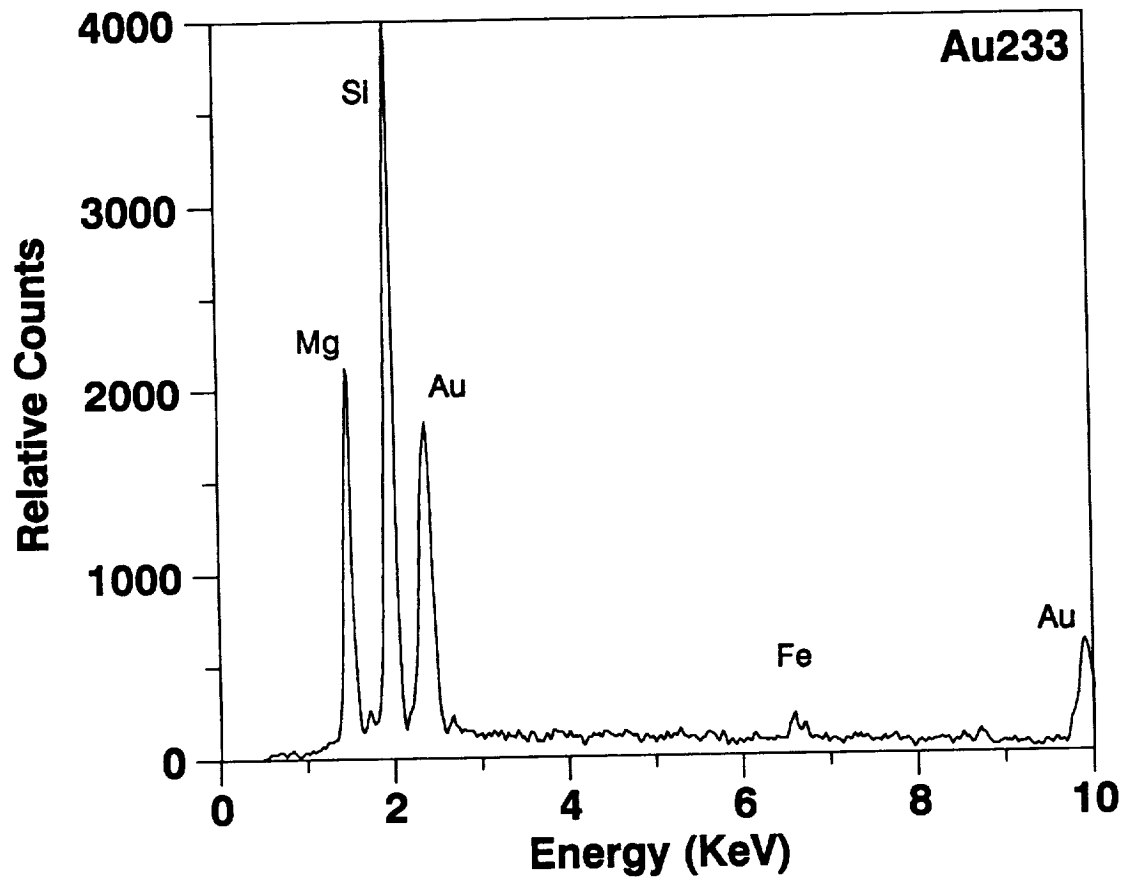


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COMPONENT: E00I
FEATURE: 233
CORE: LD-180
DIAMETER: 75 μ m
ORIGIN: Natural

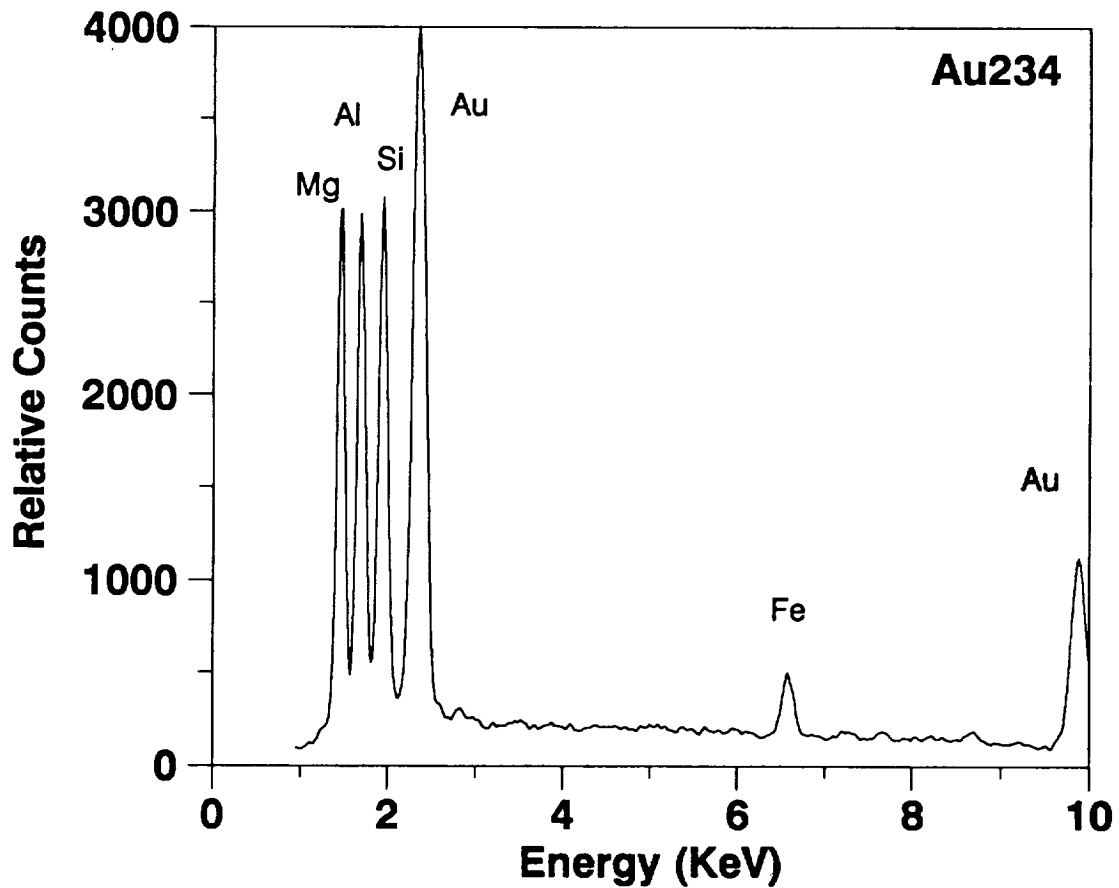


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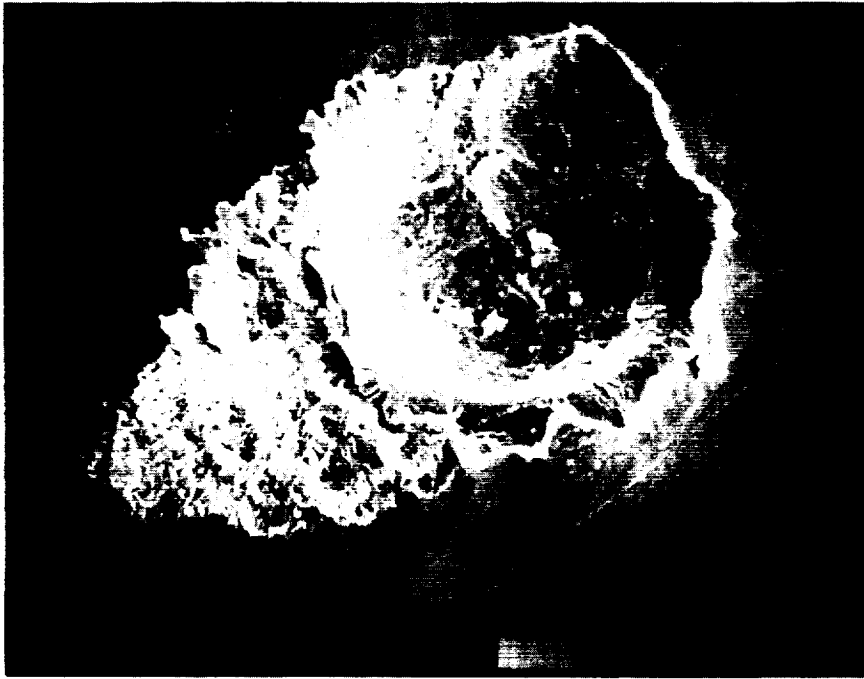


COMPONENT: EOOI
FEATURE: 234
CORE: LD-187
DIAMETER: 20 μm
ORIGIN: Natural

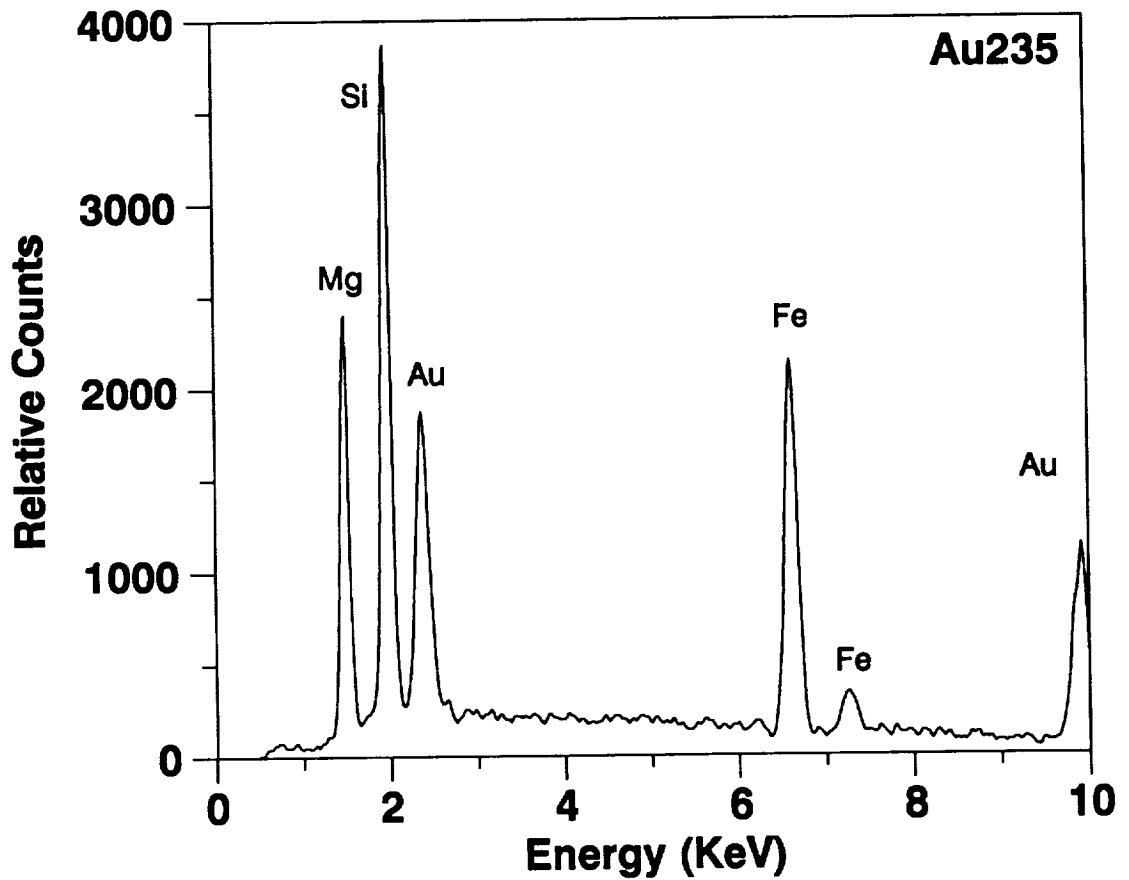


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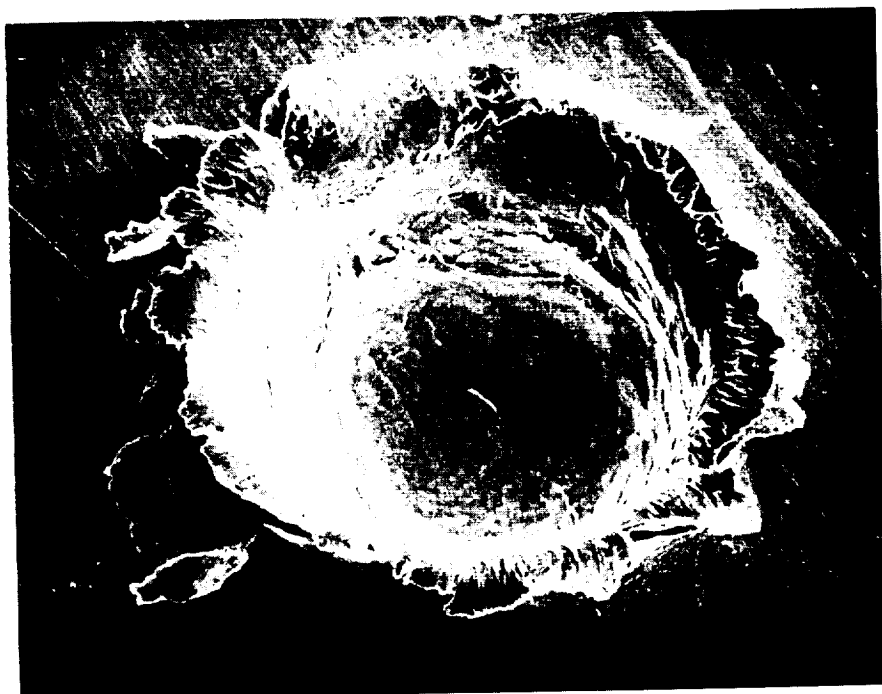


COMPONENT: EOOI
FEATURE: 235
CORE: LD-177
DIAMETER: 40 μ m
ORIGIN: Natural



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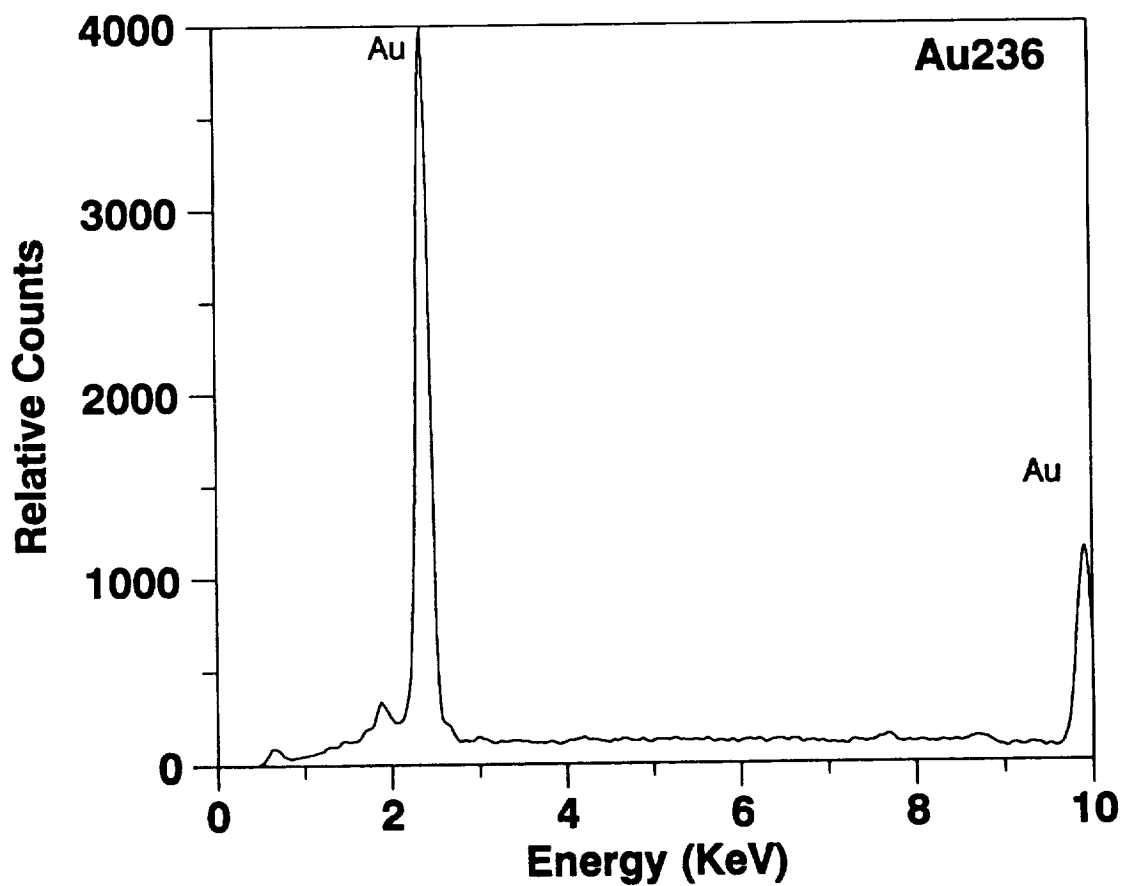
COMPONENT: EOOI

FEATURE: 236

CORE: LD-176

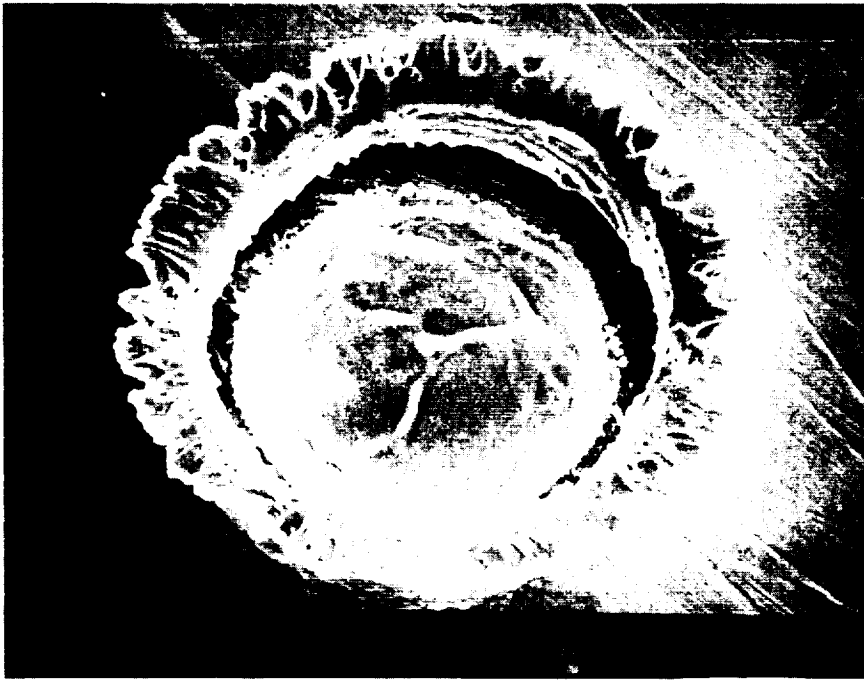
DIAMETER: 130 μm

ORIGIN: Unknown

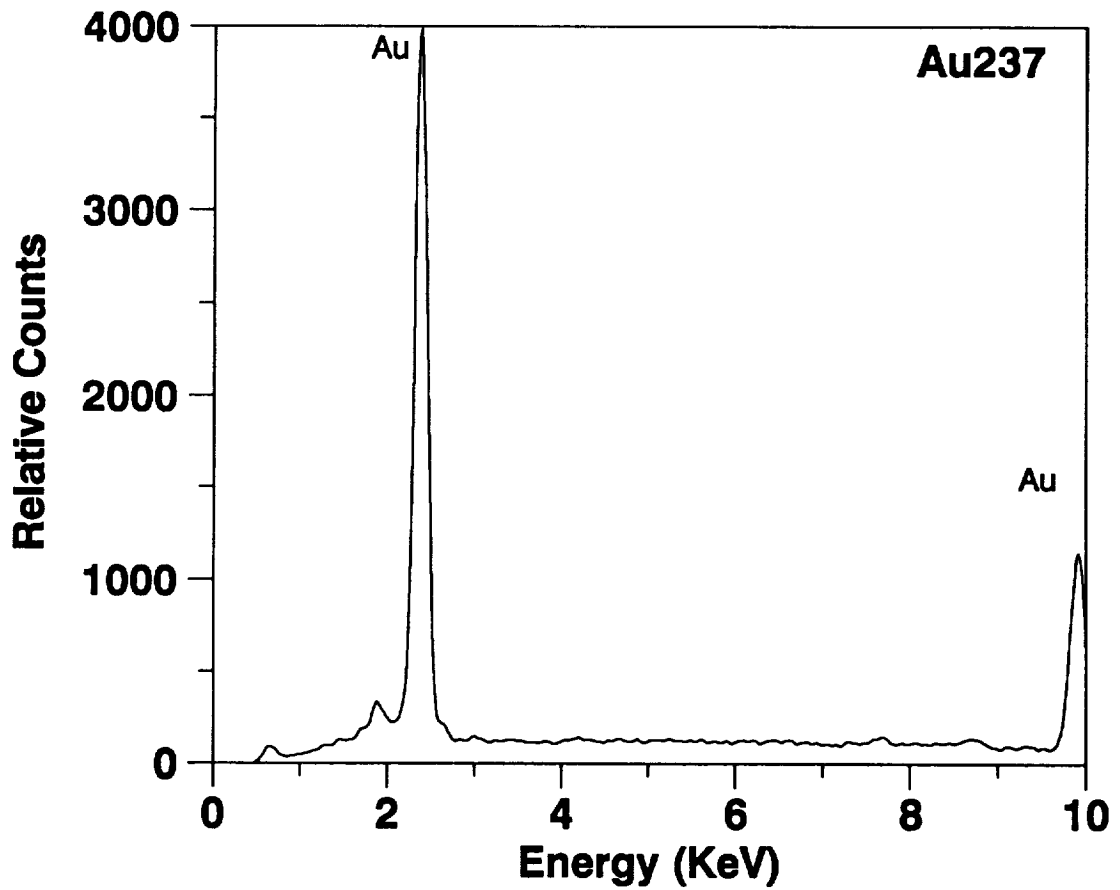


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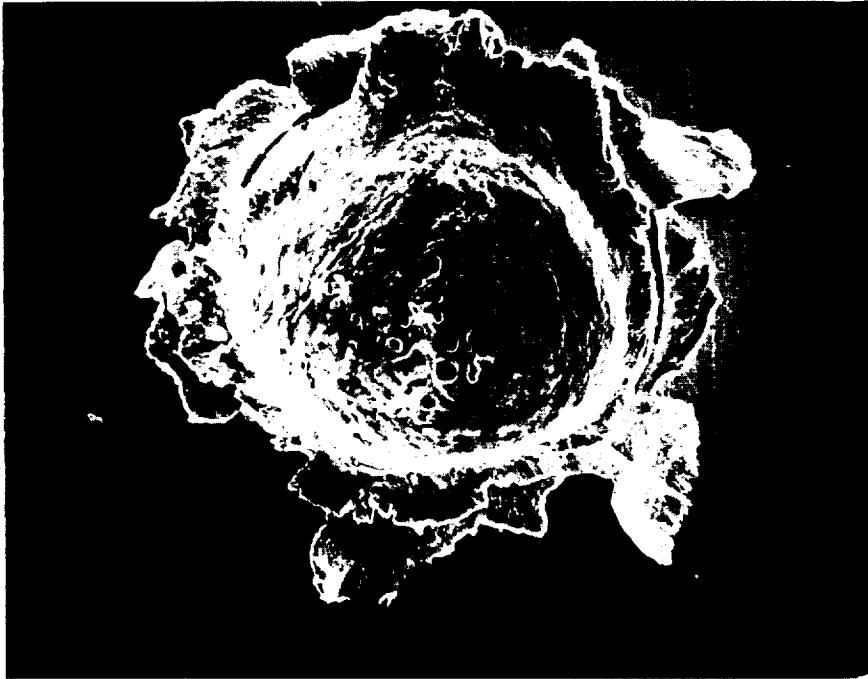


COMPONENT: E00I
FEATURE: 237
CORE: LD-176
DIAMETER: 35 μ m
ORIGIN: Unknown

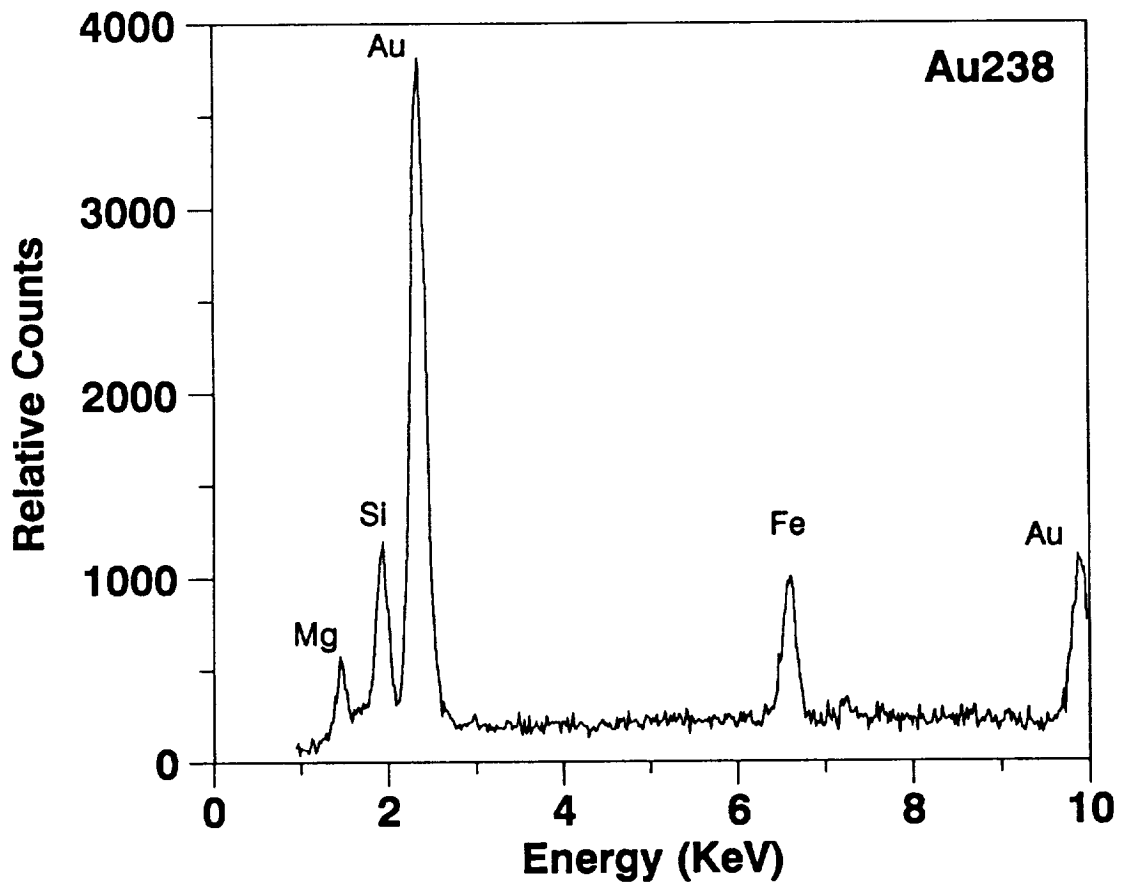


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COMPONENT: EOOI
FEATURE: 238
CORE: LD-175
DIAMETER: 100 μ m
ORIGIN: Natural

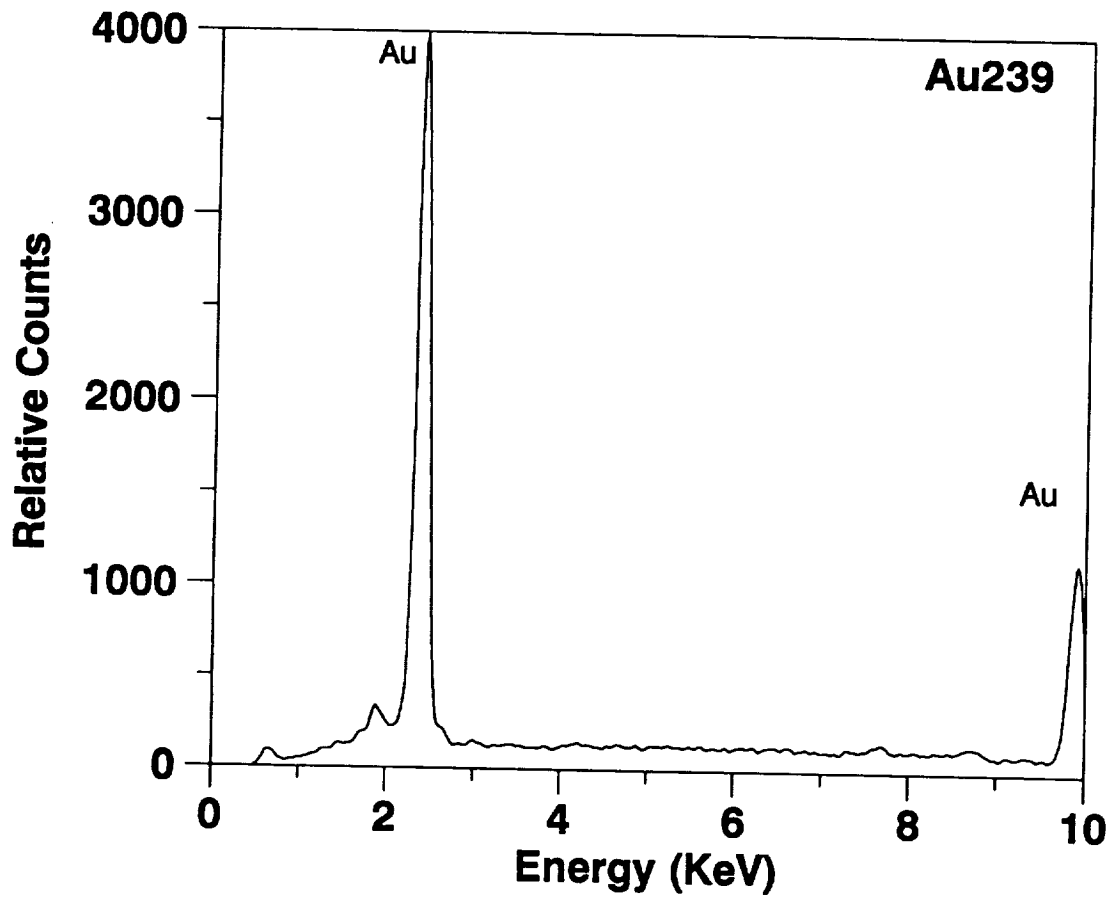


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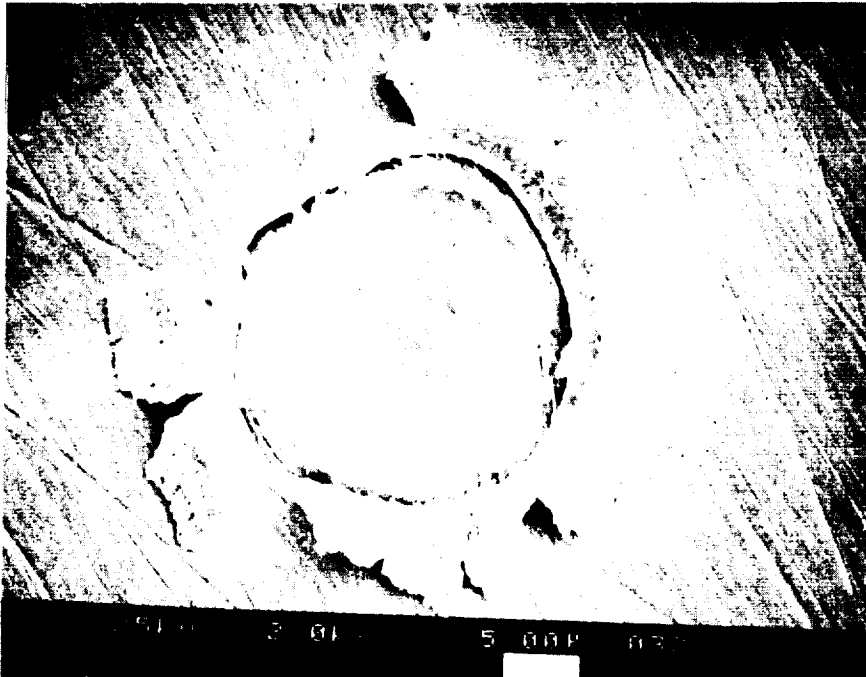


COMPONENT: EOOI
FEATURE: 239
CORE: LD-173
DIAMETER: 160 μ m
ORIGIN: Unknown



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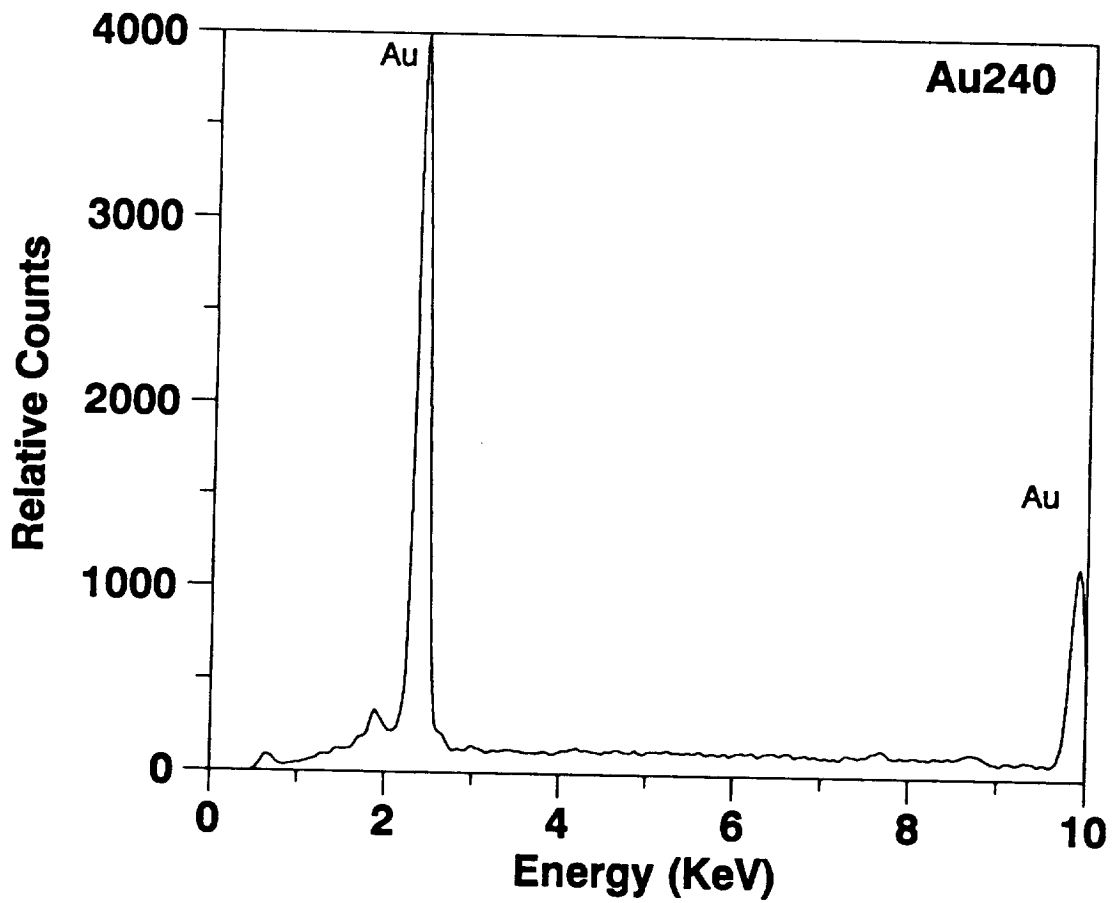
COMPONENT: E001

FEATURE: 240

CORE: LD-182

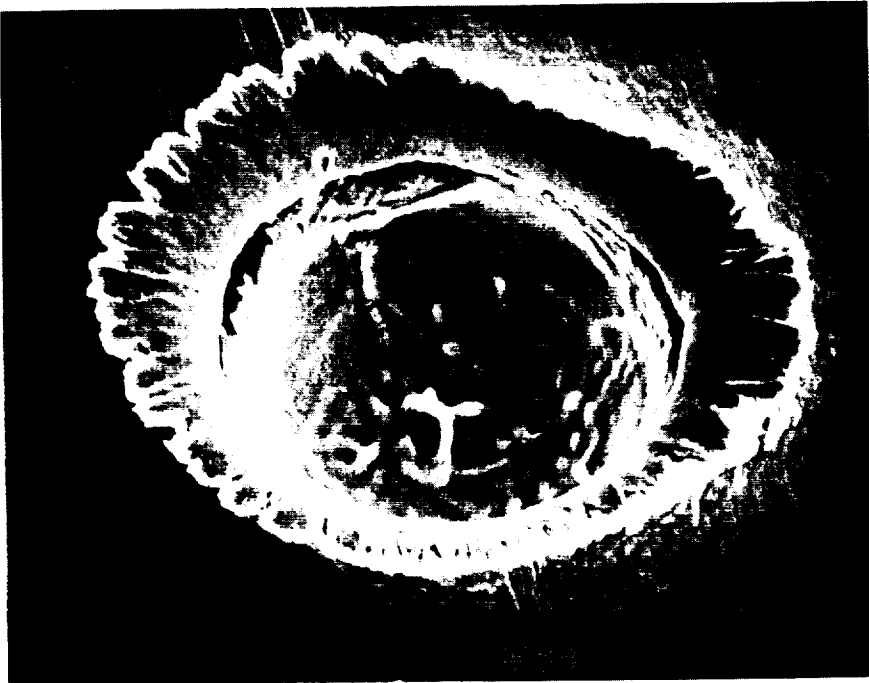
DIAMETER: 15 μ m

ORIGIN: Unknown

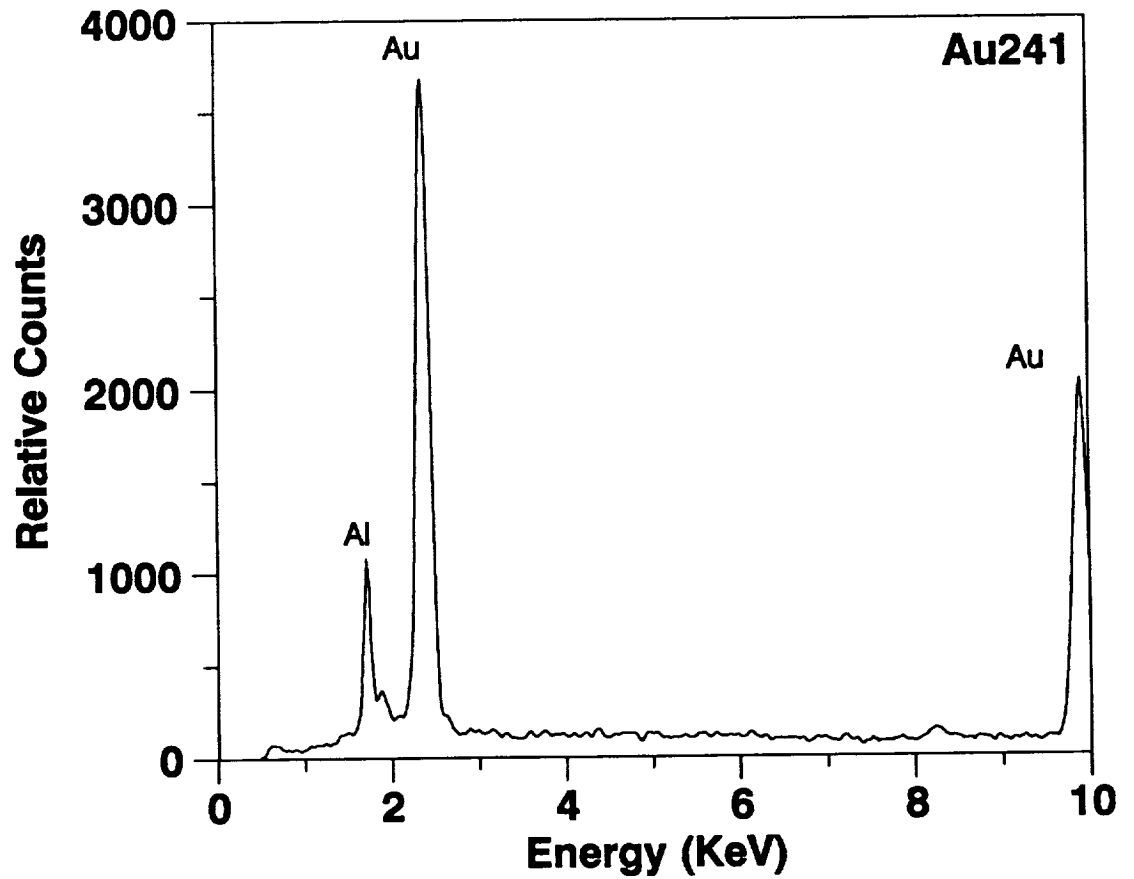


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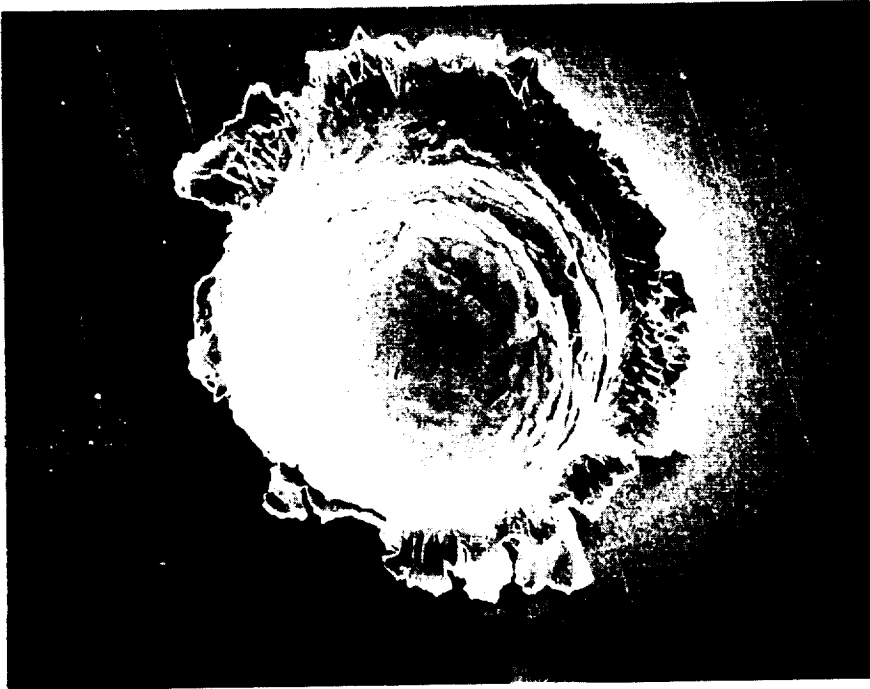


COMPONENT: EOOI
FEATURE: 241
CORE: LD-174
DIAMETER: 20 μ m
ORIGIN: Man-made



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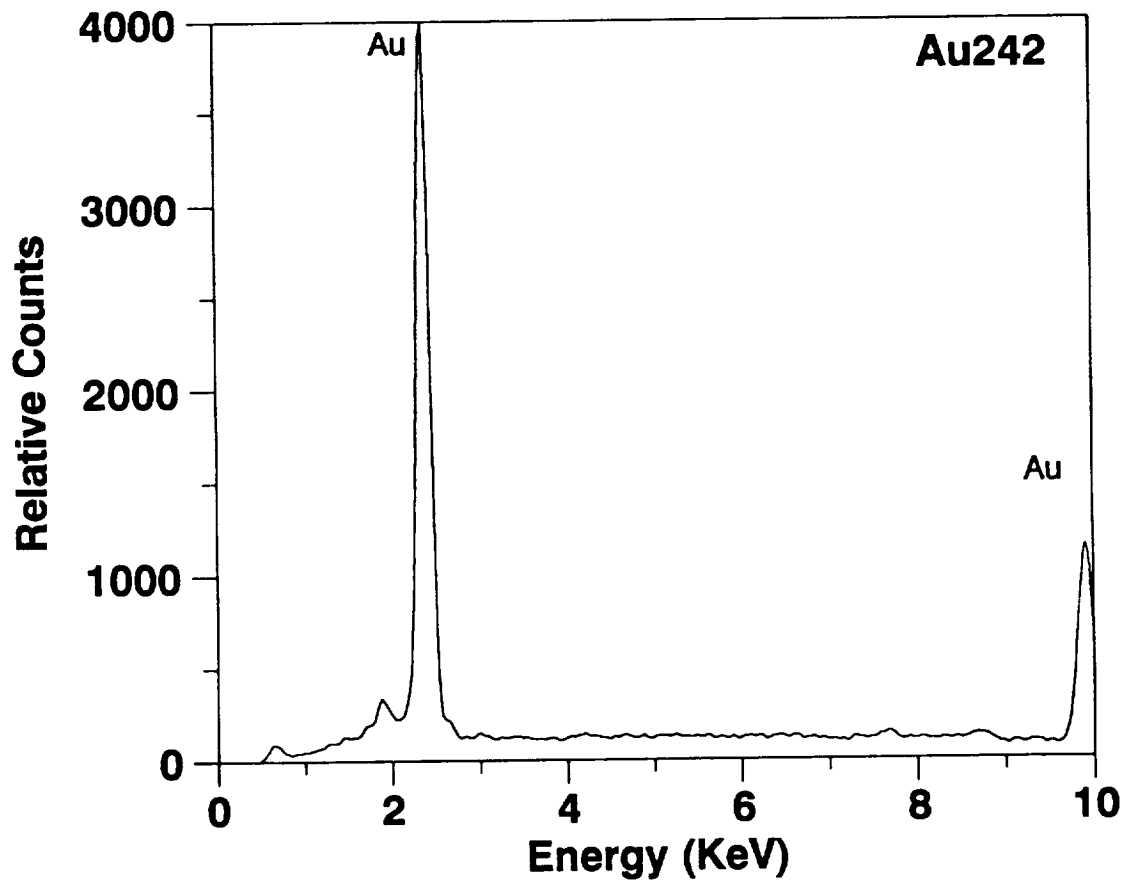
COMPONENT: E001

FEATURE: 242

CORE: LD-183

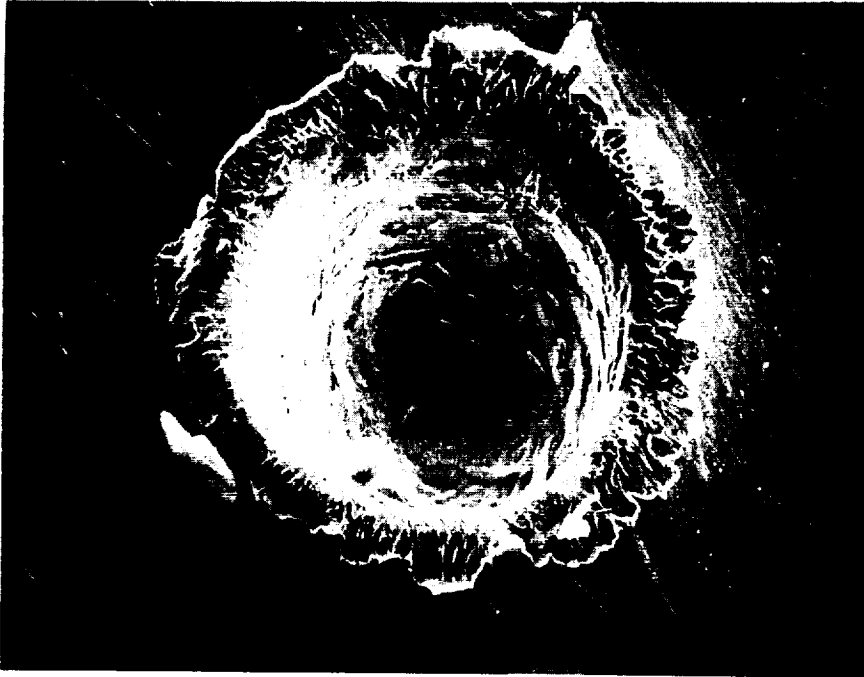
DIAMETER: 95 μ m

ORIGIN: Unknown

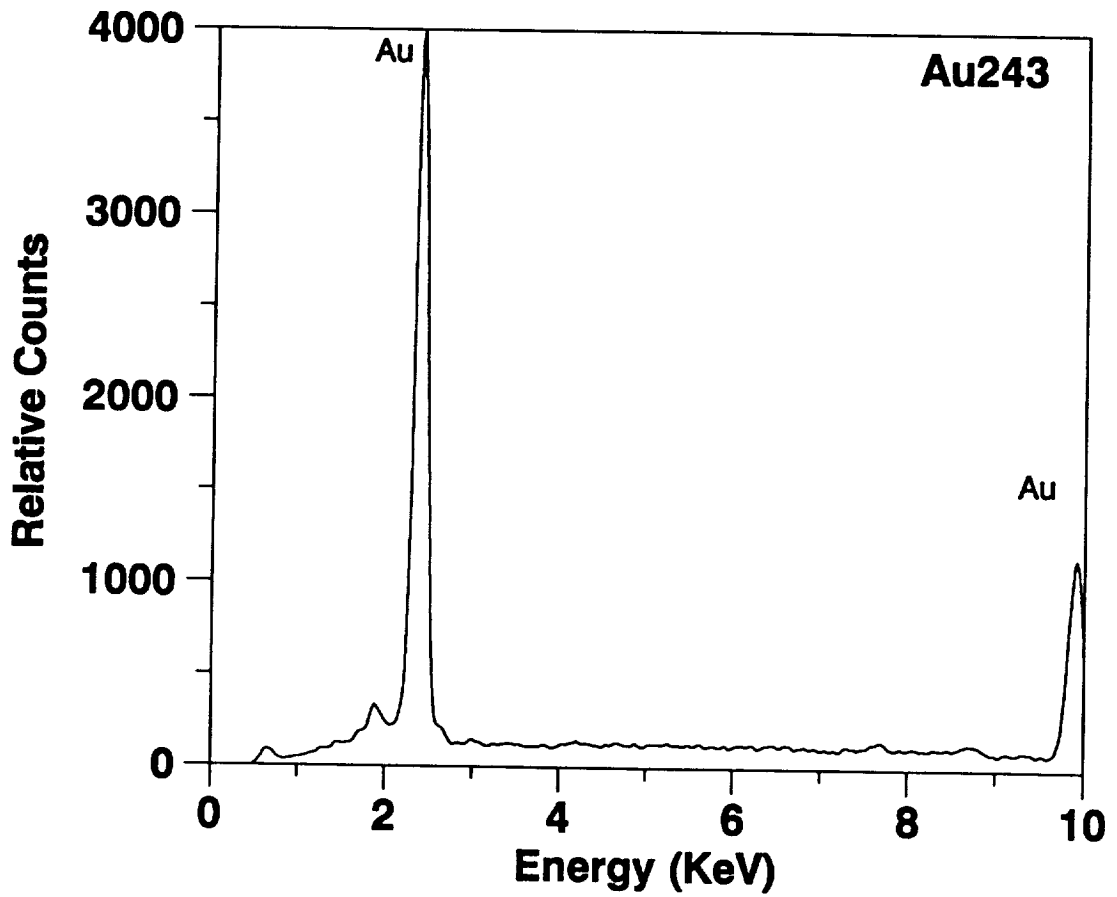


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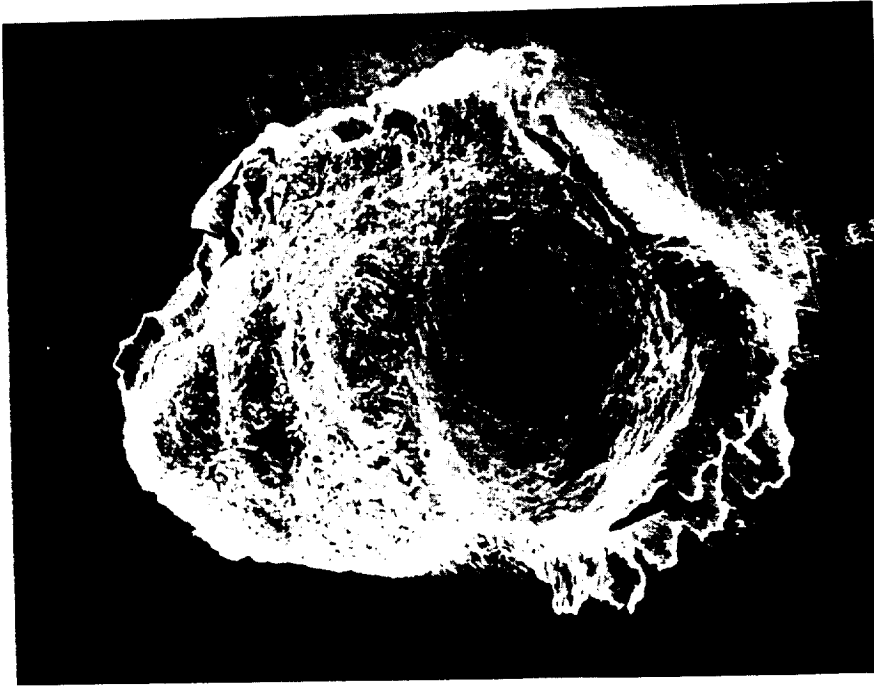


COMPONENT: E001
FEATURE: 243
CORE: LD-184
DIAMETER: 125 μ m
ORIGIN: Unknown

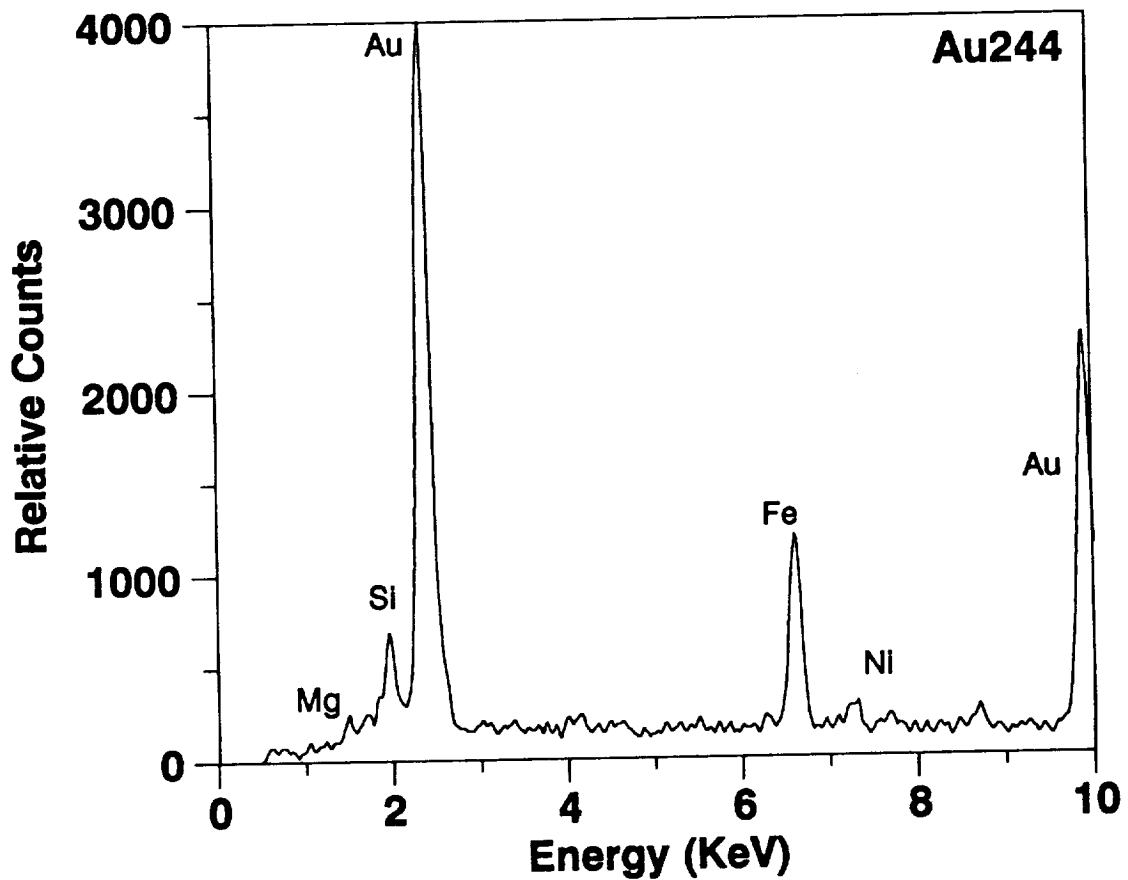


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COMPONENT: E001
FEATURE: 244
CORE: LD-185
DIAMETER: 80 μ m
ORIGIN: Natural



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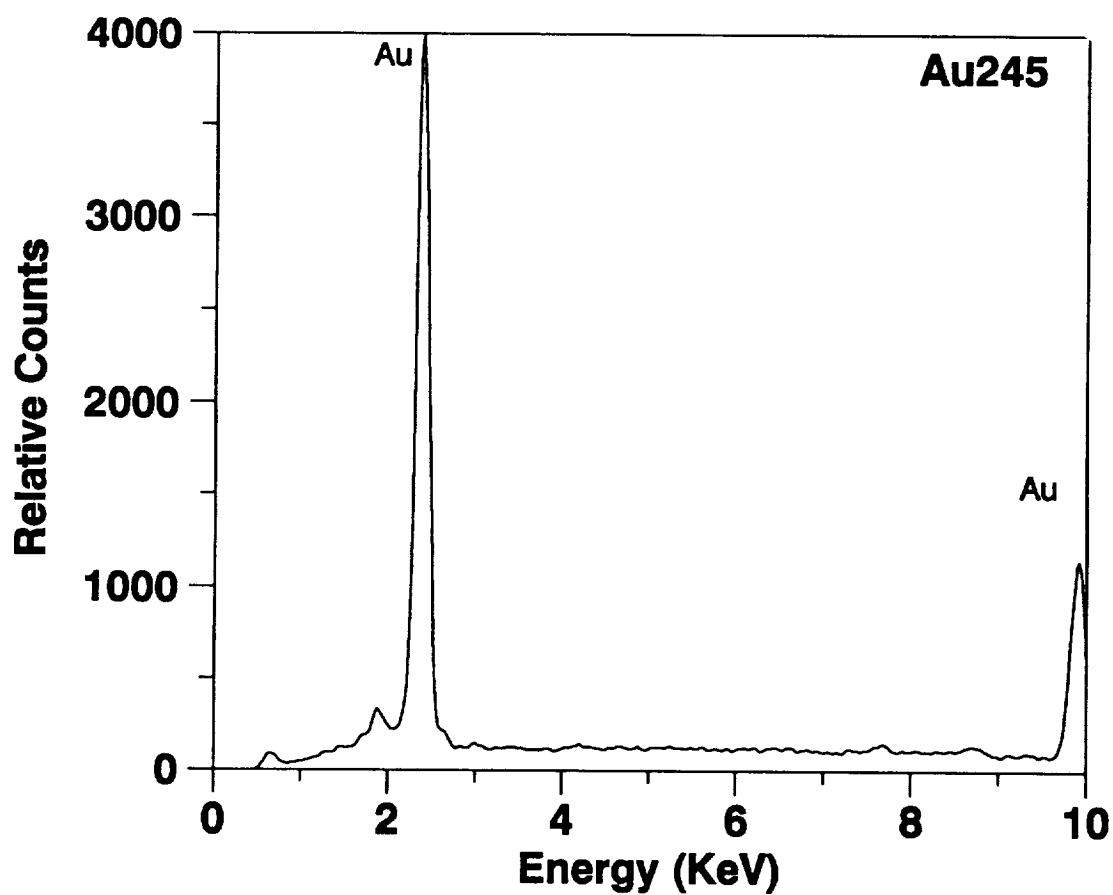
COMPONENT: E00I

FEATURE: 245

CORE: LD-186

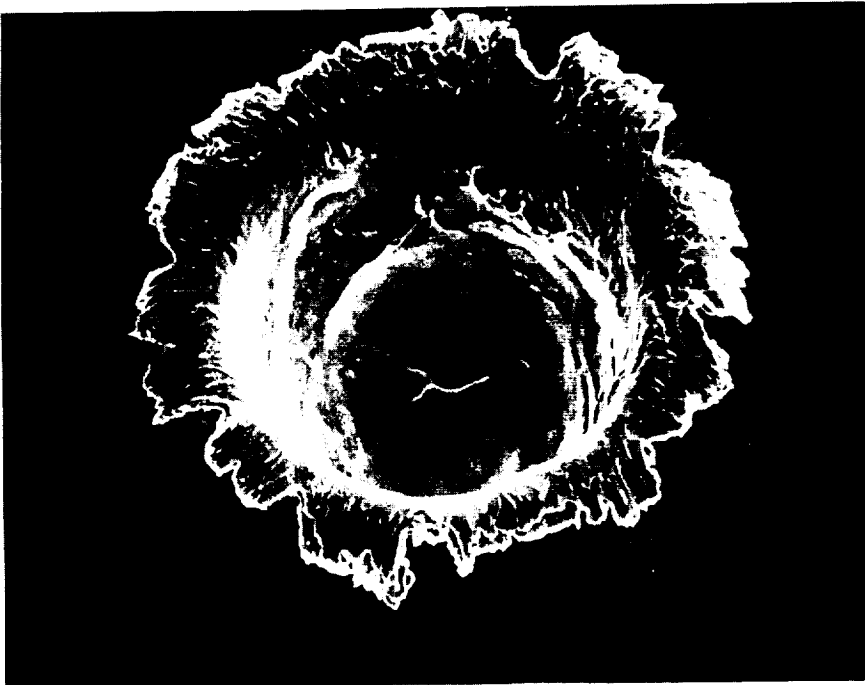
DIAMETER: 30 μ m

ORIGIN: Unknown



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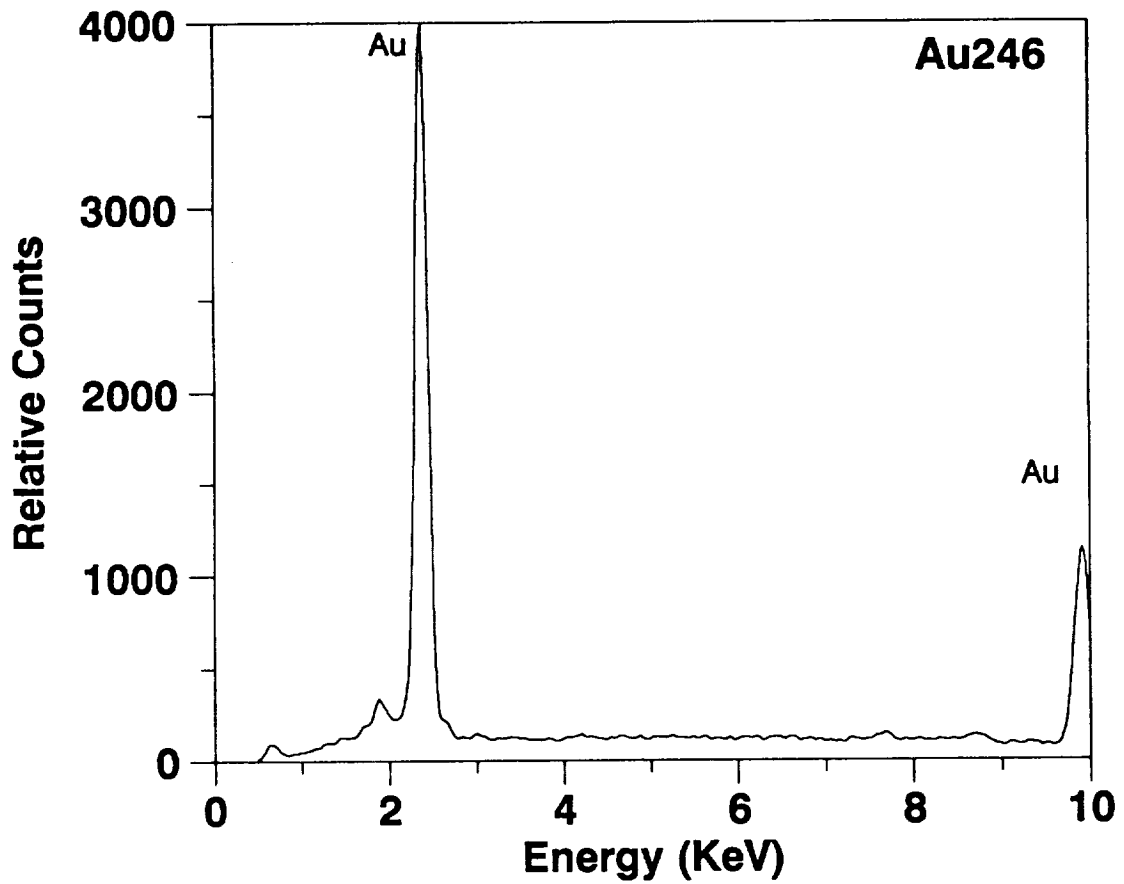
COMPONENT: EOOJ

FEATURE: 246

CORE: LD-227

DIAMETER: 55 μm

ORIGIN: Unknown



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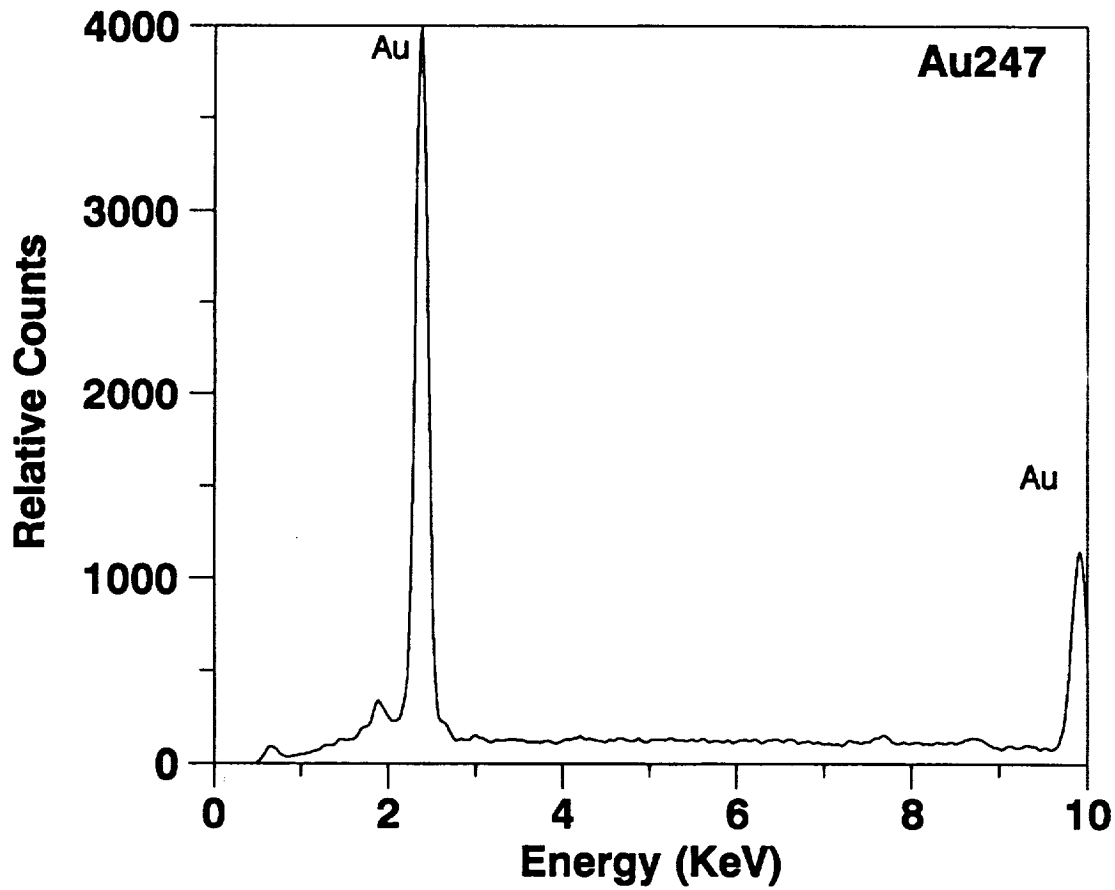
COMPONENT: EOOJ

FEATURE: 247

CORE: LD-201

DIAMETER: 15 μ m

ORIGIN: Unknown

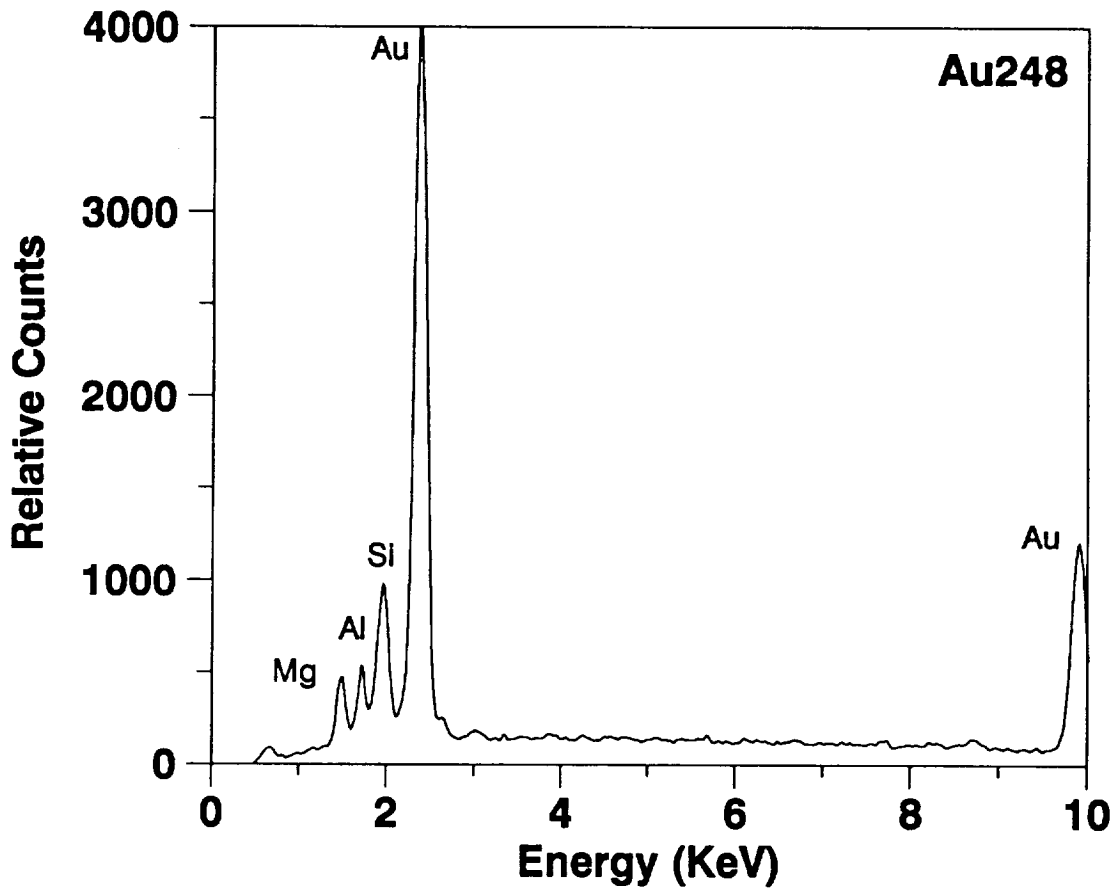


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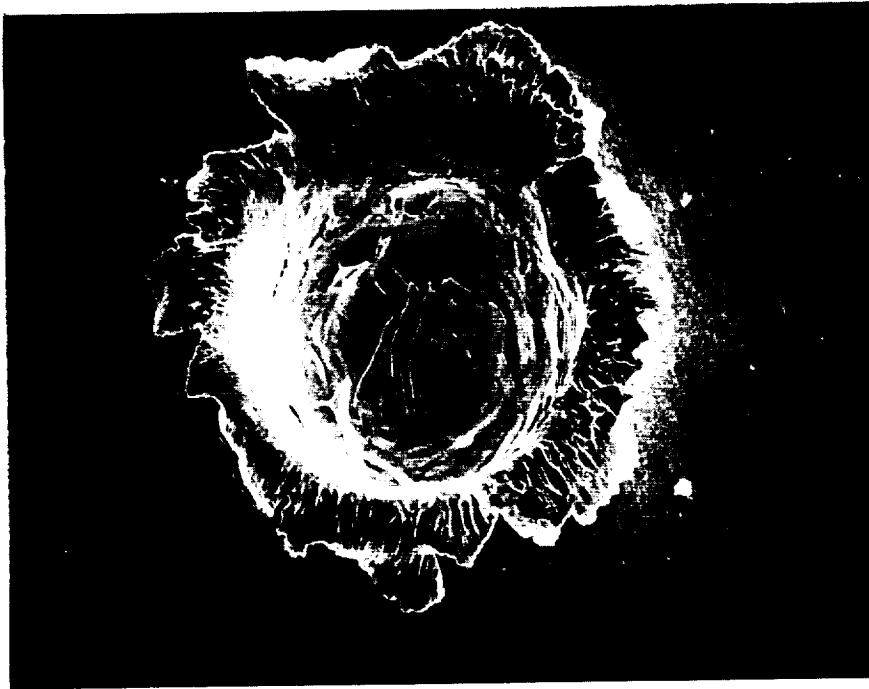


COMPONENT: EOOJ
FEATURE: 248
CORE: LD-202
DIAMETER: 20 μ m
ORIGIN: Natural

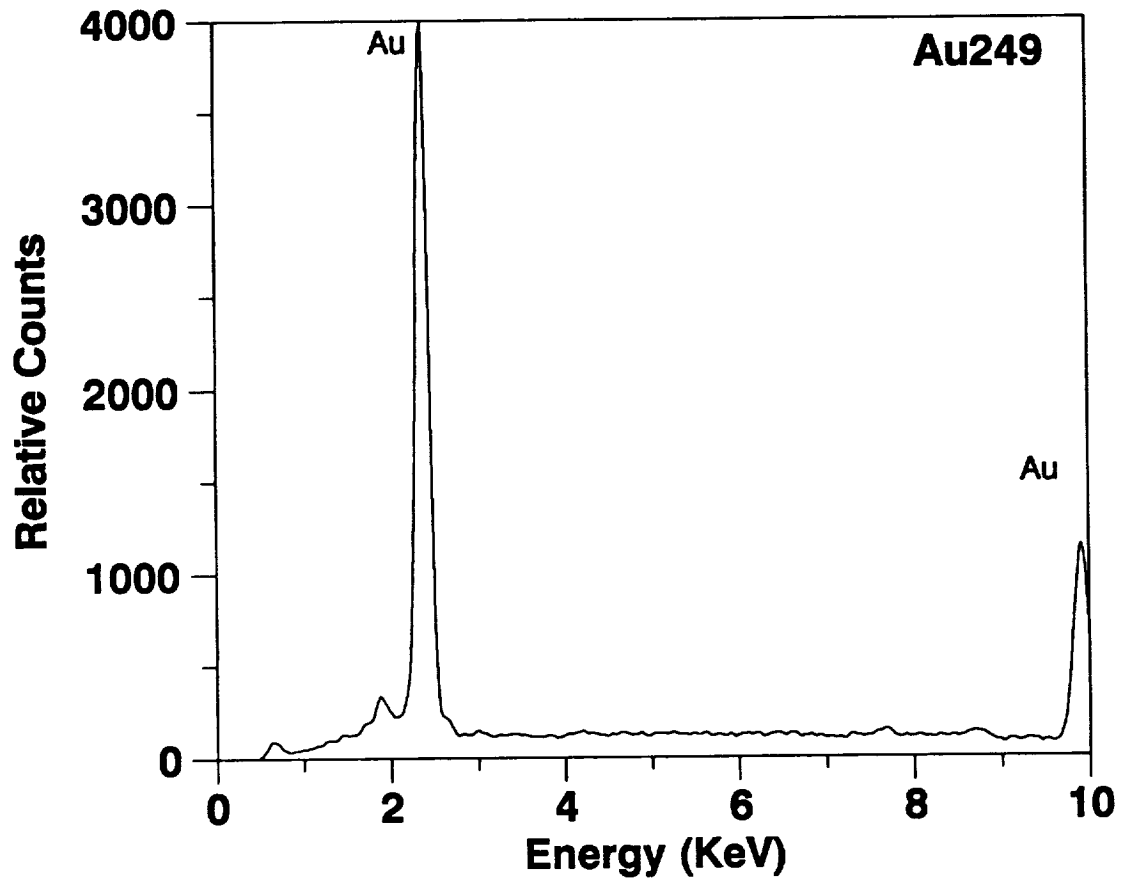


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COMPONENT: EOOJ
FEATURE: 249
CORE: LD-203
DIAMETER: 105 μ m
ORIGIN: Unknown

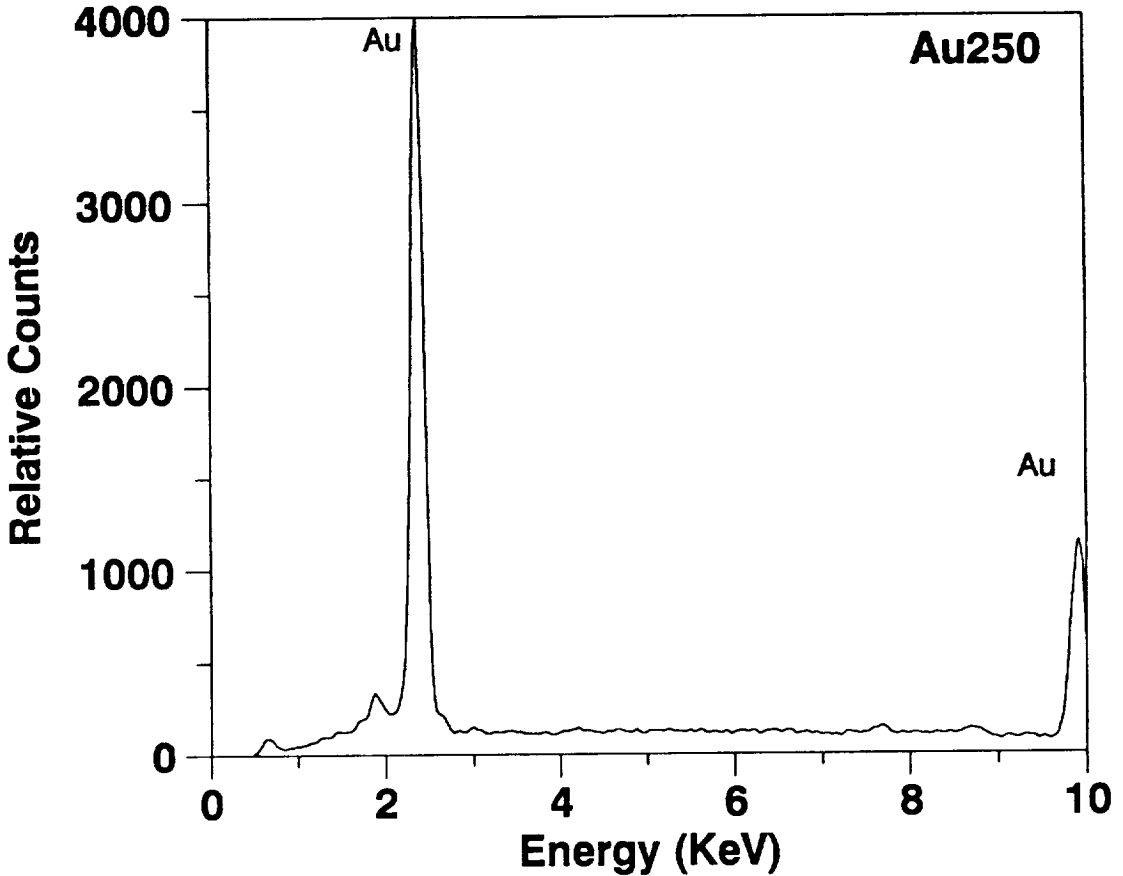


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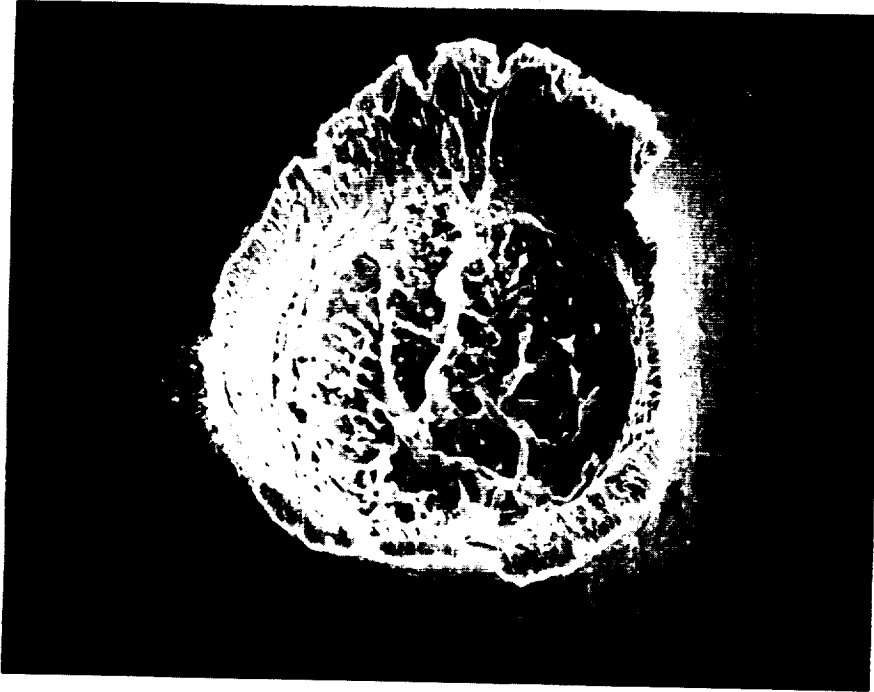


COMPONENT: EOOJ
FEATURE: 250
CORE: LD-204
DIAMETER: 55 μm
ORIGIN: Unknown

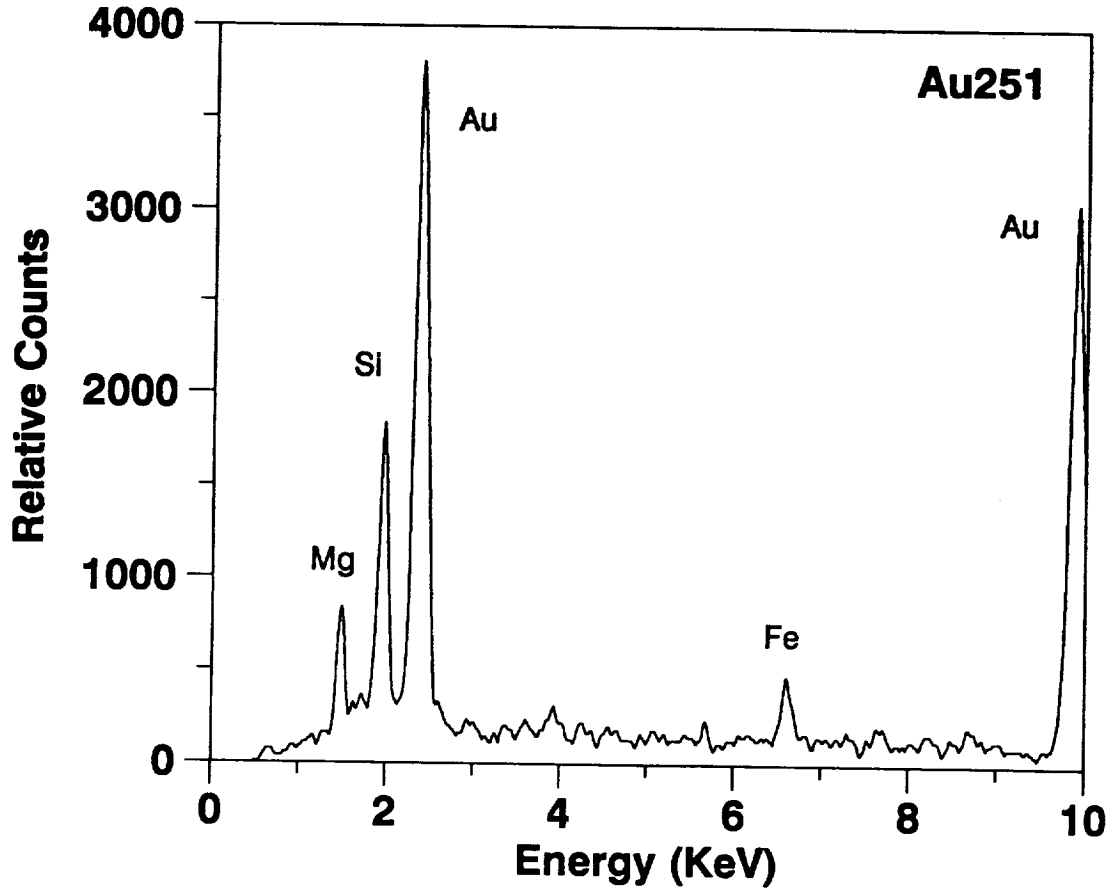


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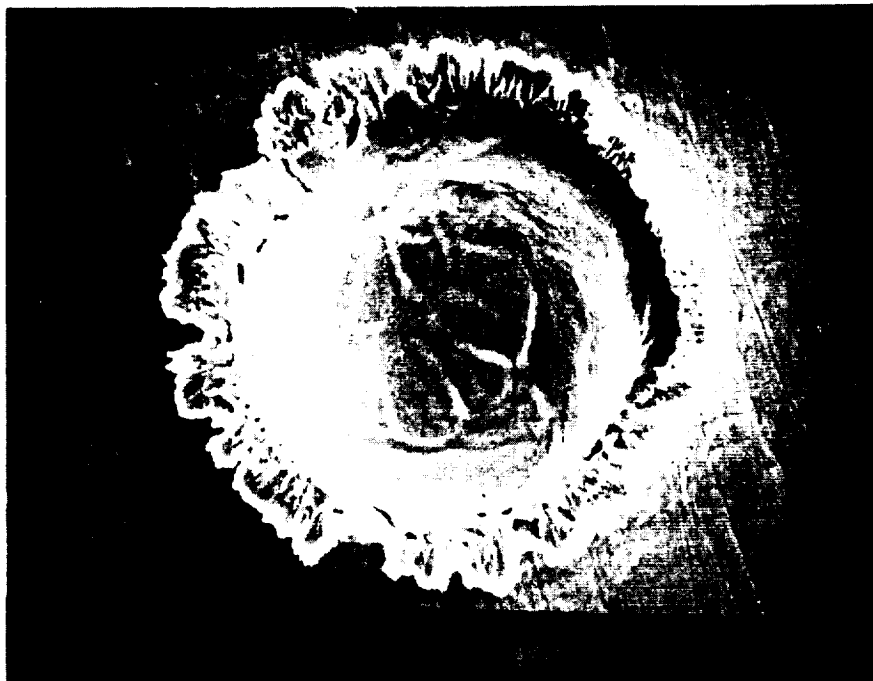


COMPONENT: EOOJ
FEATURE: 251
CORE: LD-205
DIAMETER: 45 μ m
ORIGIN: Natural



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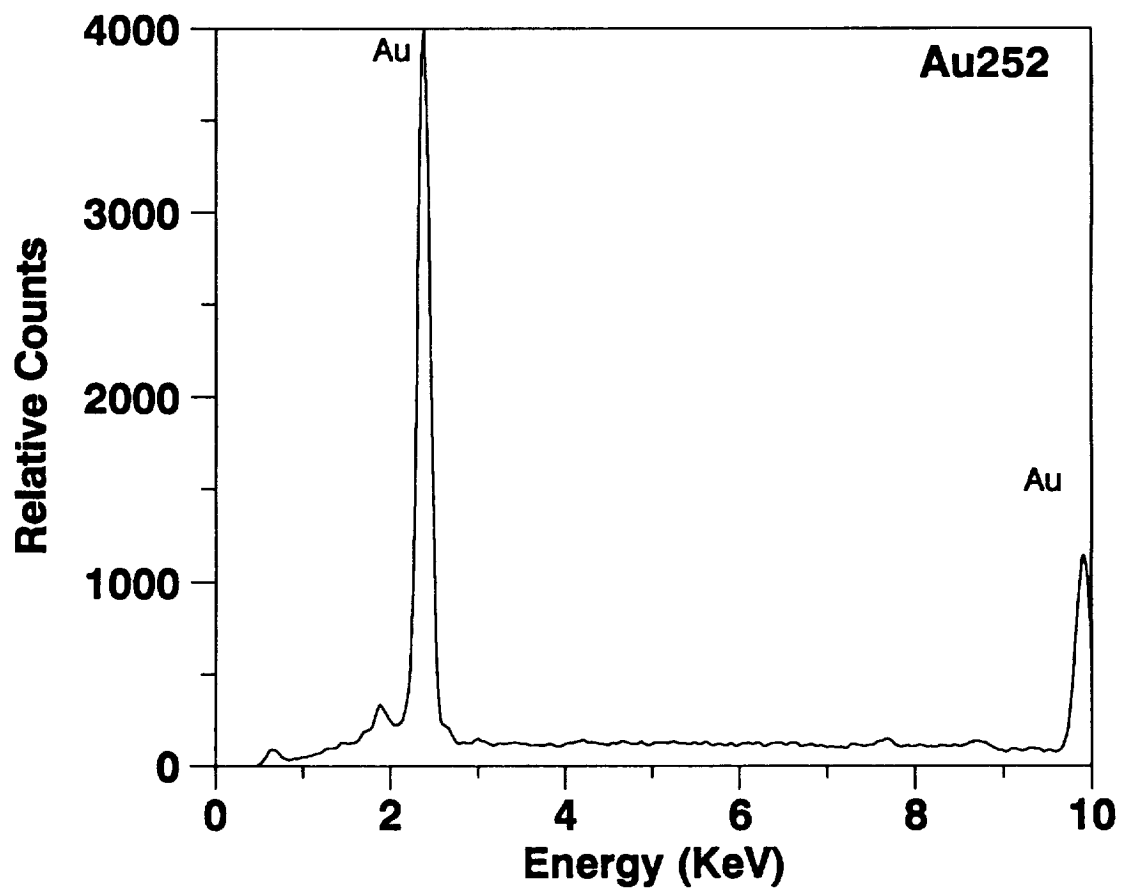
COMPONENT: E00J

FEATURE: 252

CORE: LD-206

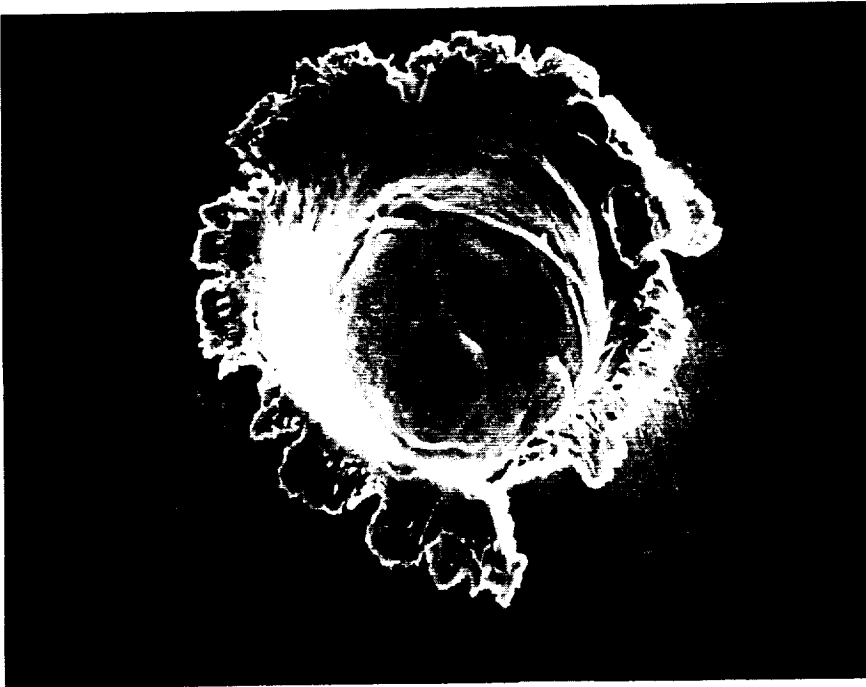
DIAMETER: 25 μm

ORIGIN: Unknown

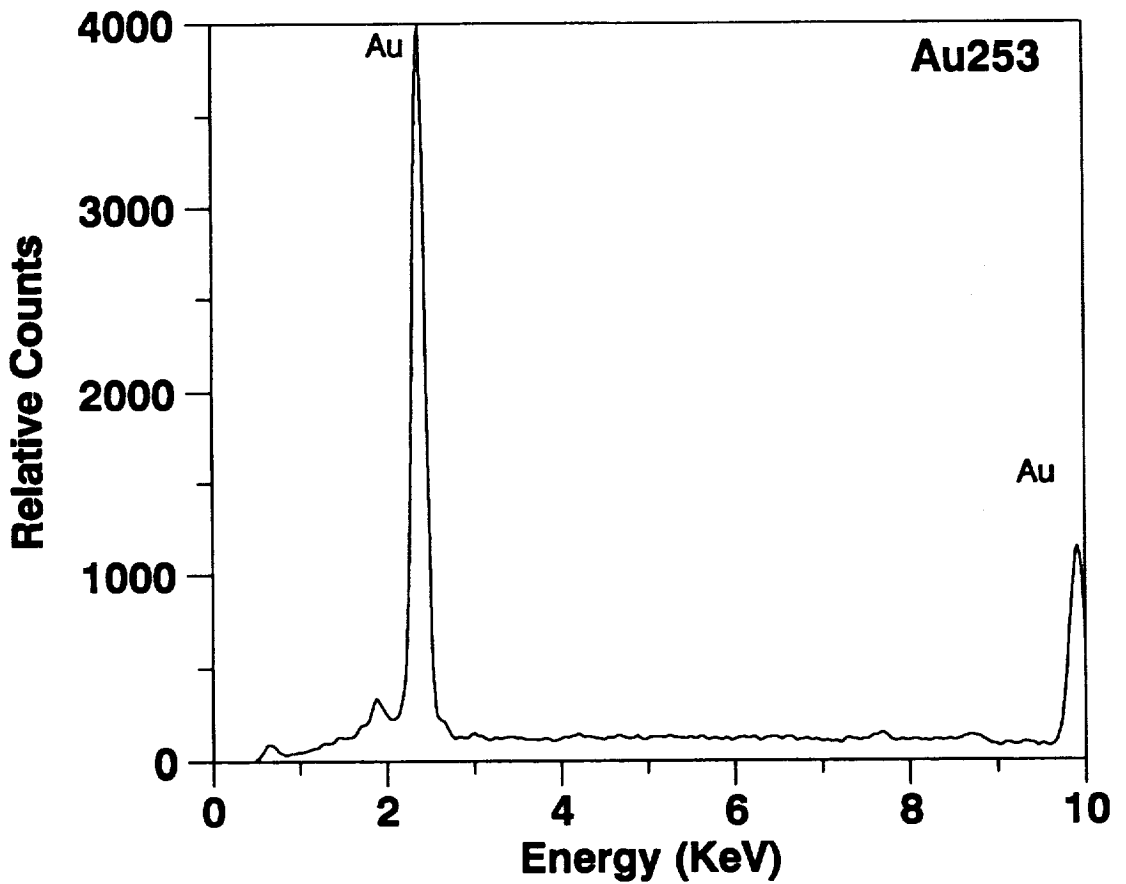


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COMPONENT: EOOJ
FEATURE: 253
CORE: LD-207
DIAMETER: 30 μ m
ORIGIN: Unknown



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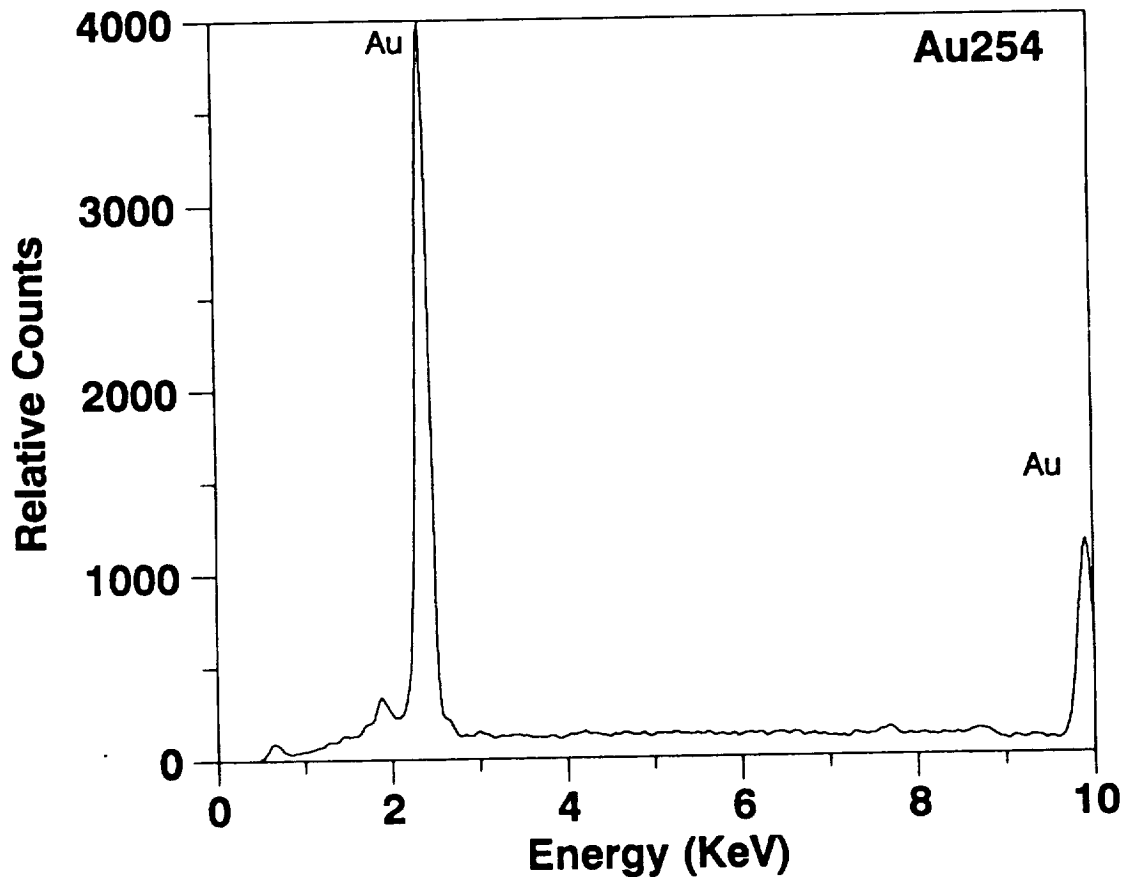
COMPONENT: EOOJ

FEATURE: 254

CORE: LD-208

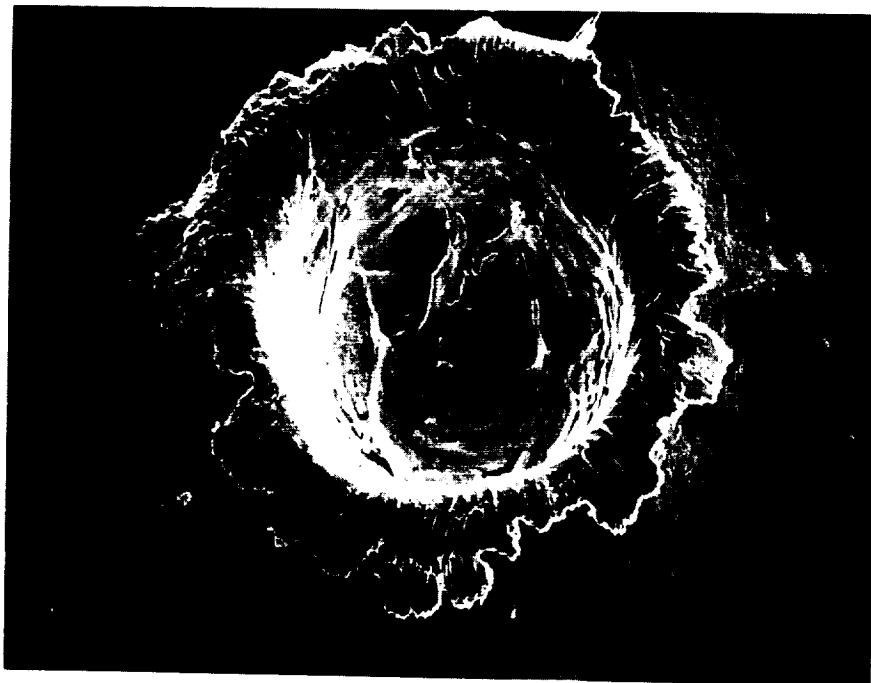
DIAMETER: 45 μm

ORIGIN: Unknown

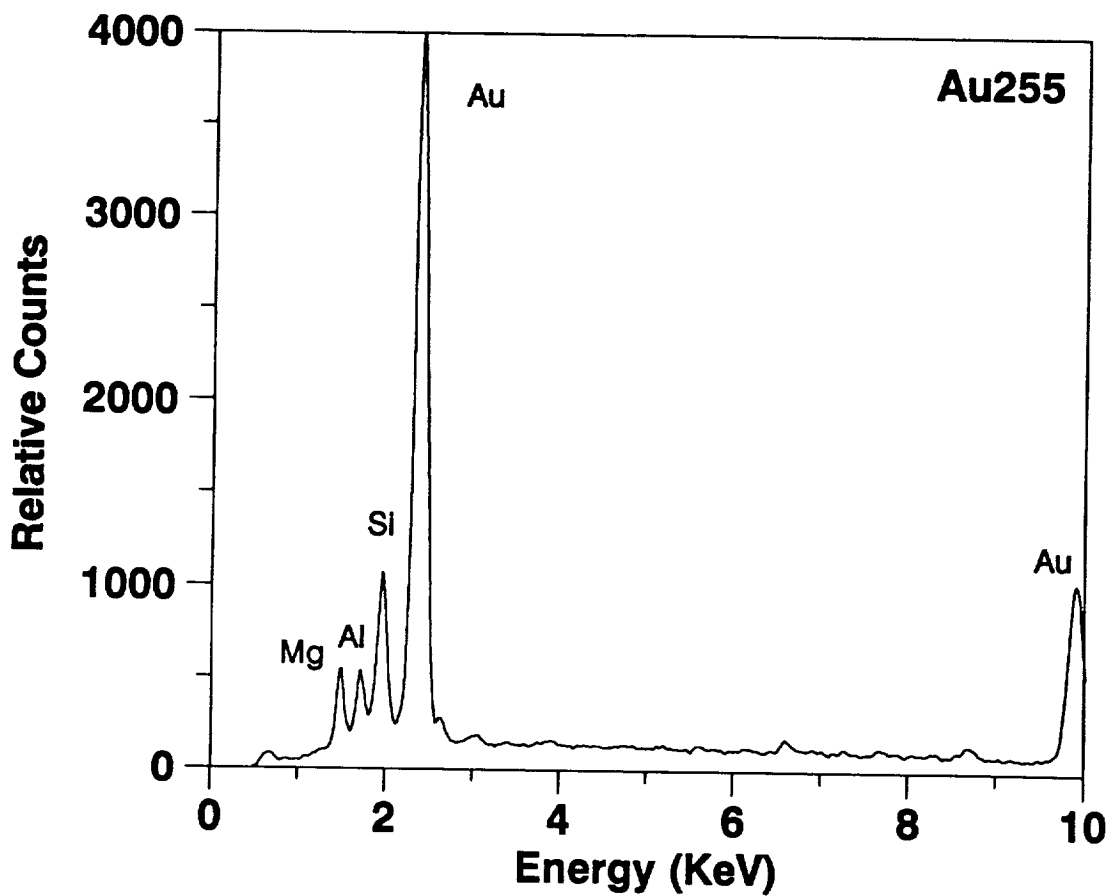


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COMPONENT: EOOJ
FEATURE: 255
CORE: LD-209
DIAMETER: 100 μ m
ORIGIN: Natural

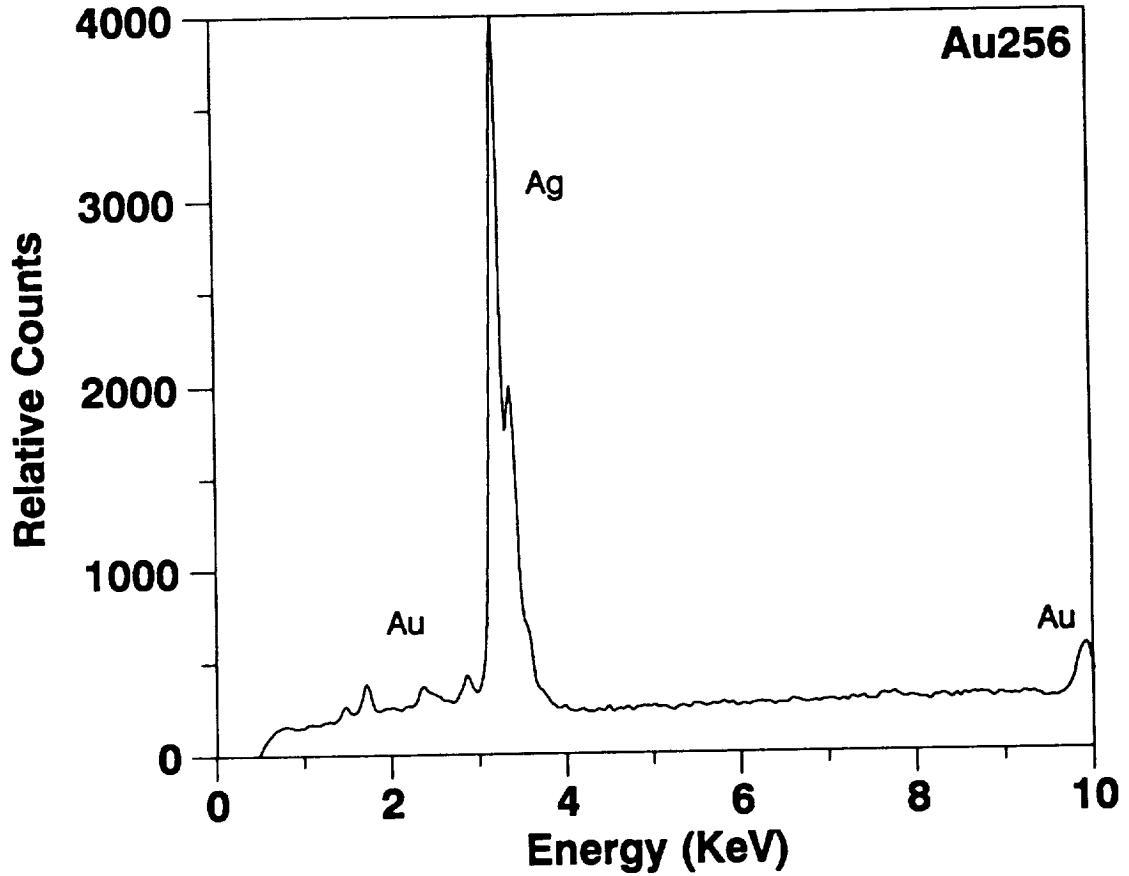


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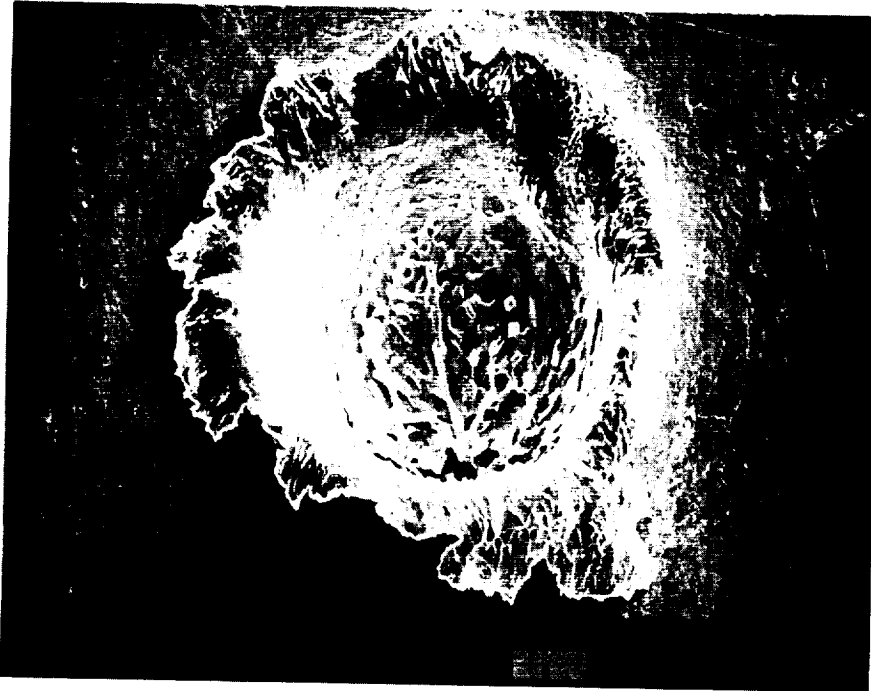


COMPONENT: EOOJ
FEATURE: 256
CORE: LD-210
DIAMETER: 60 μ m
ORIGIN: Man-made

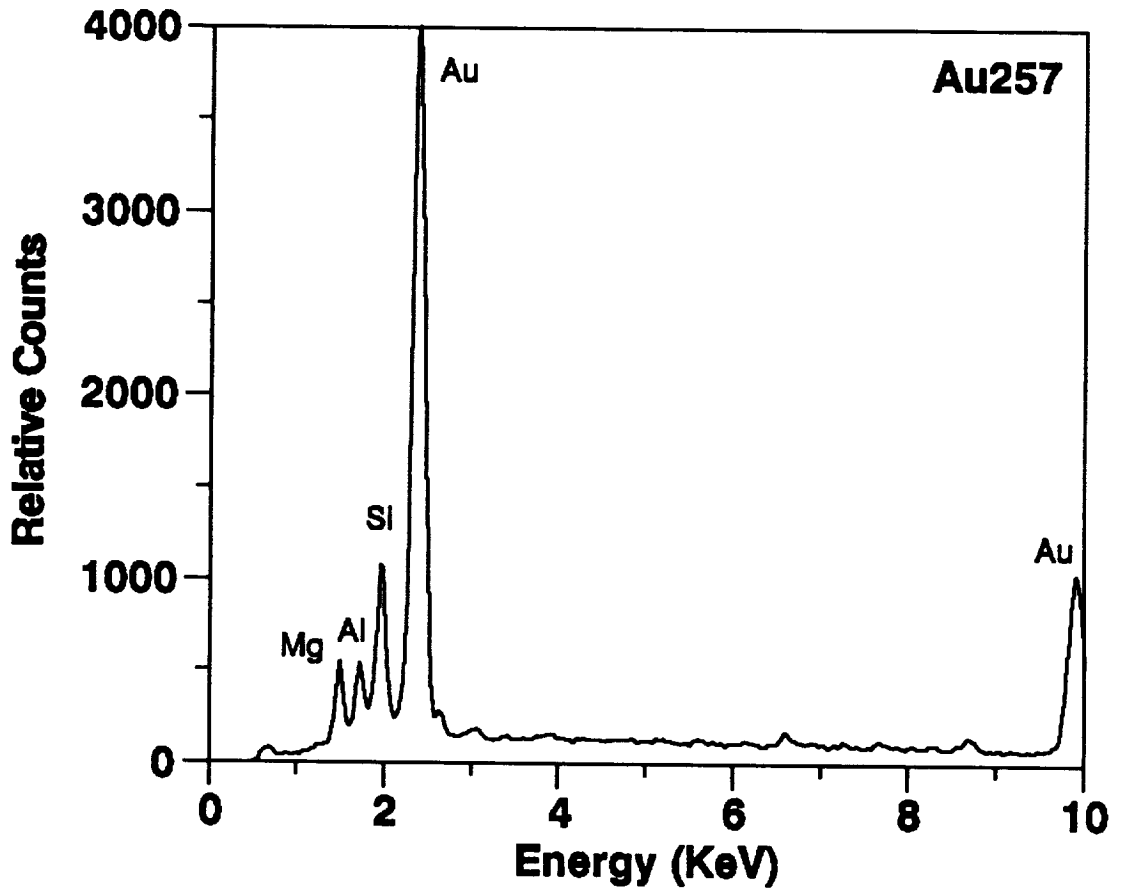


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COMPONENT: EOOJ
FEATURE: 257
CORE: LD-211
DIAMETER: 95 μm
ORIGIN: Natural

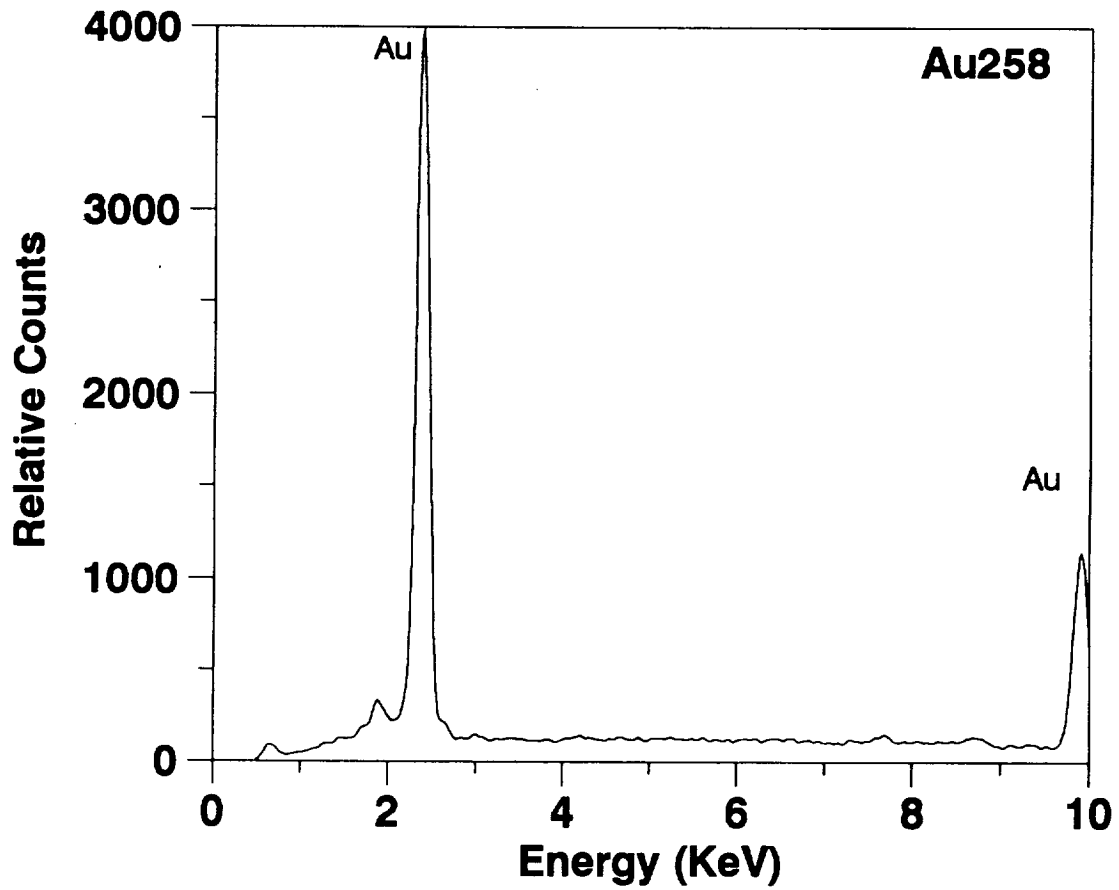


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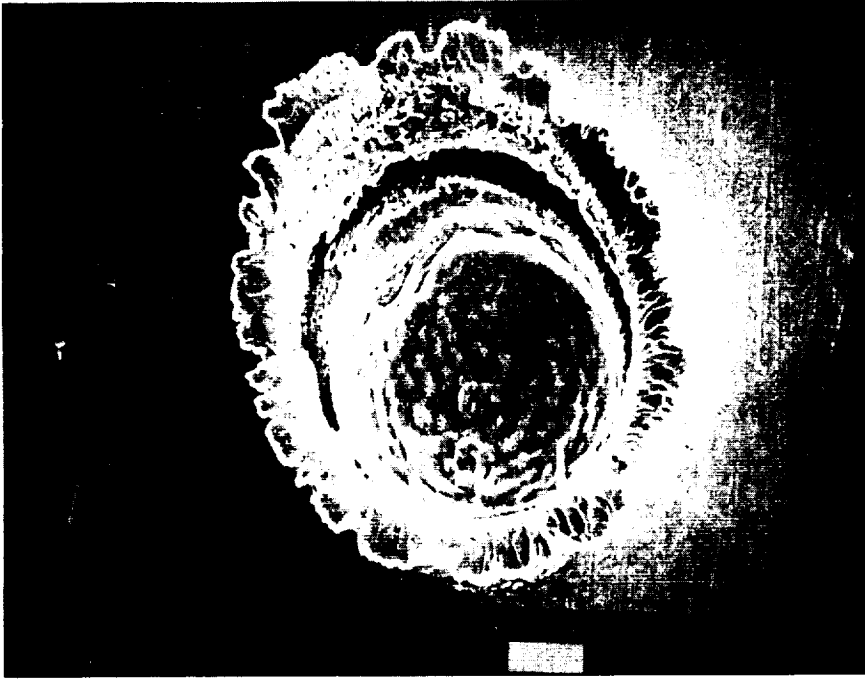


COMPONENT: EOOJ
FEATURE: 258
CORE: LD-226
DIAMETER: 45 μm
ORIGIN: Unknown

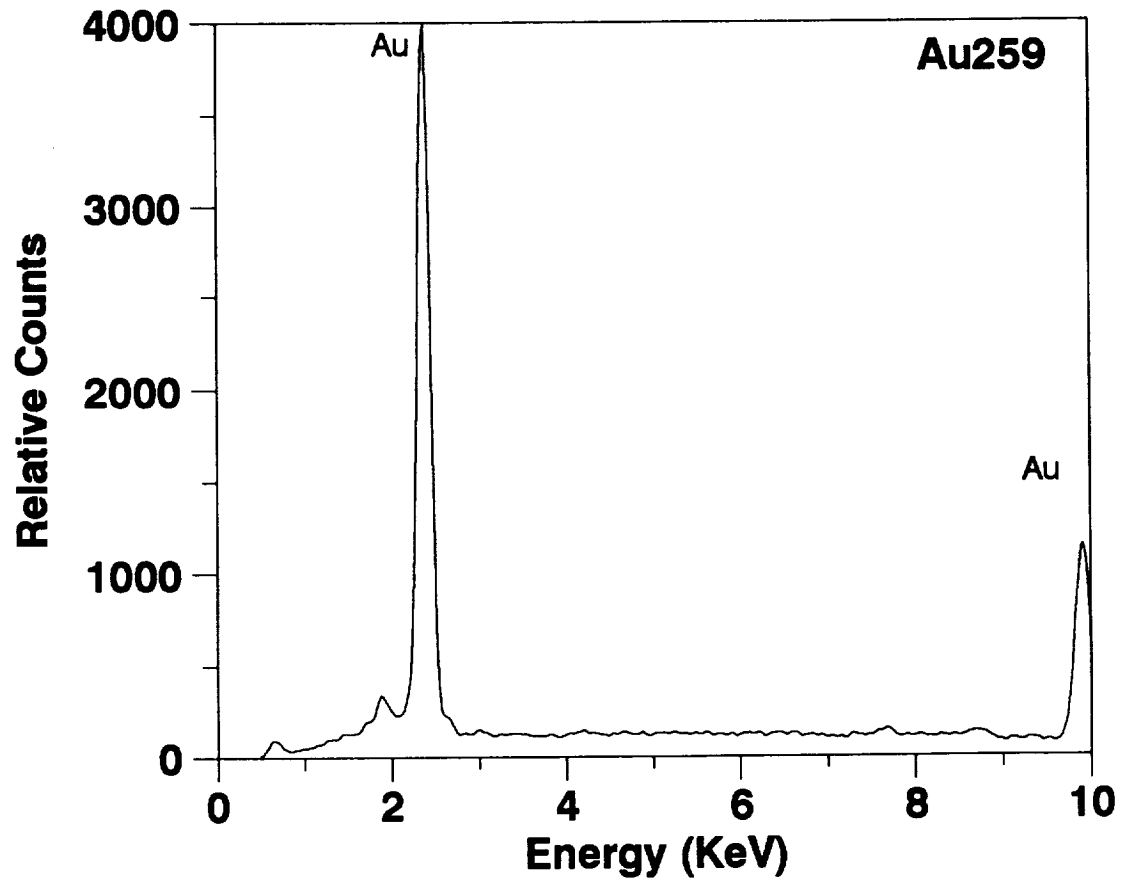


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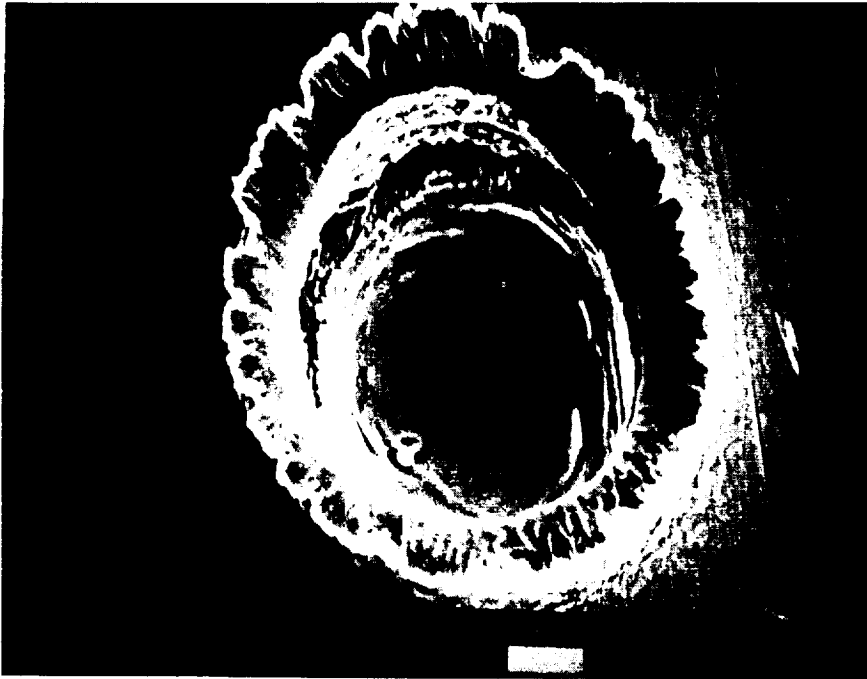


COMPONENT: EOOJ
FEATURE: 259
CORE: LD-212
DIAMETER: 50 μm
ORIGIN: Unknown

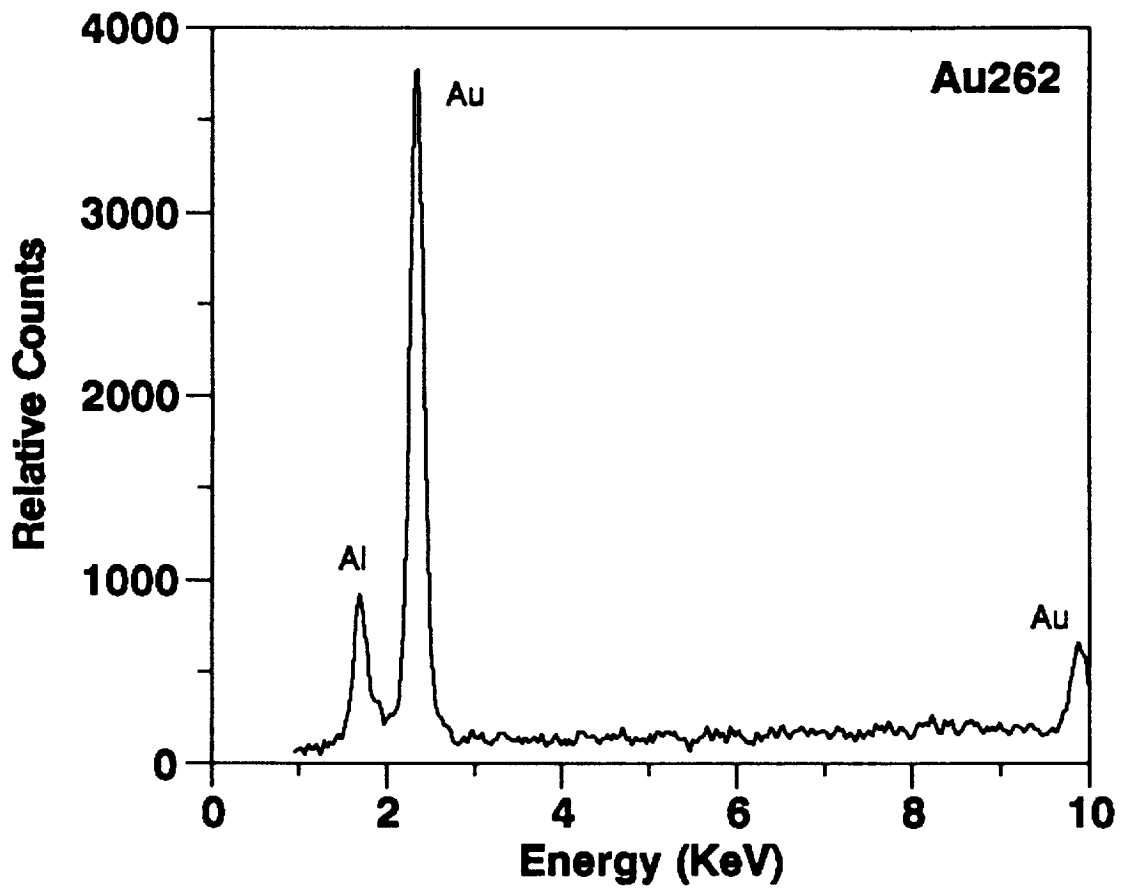


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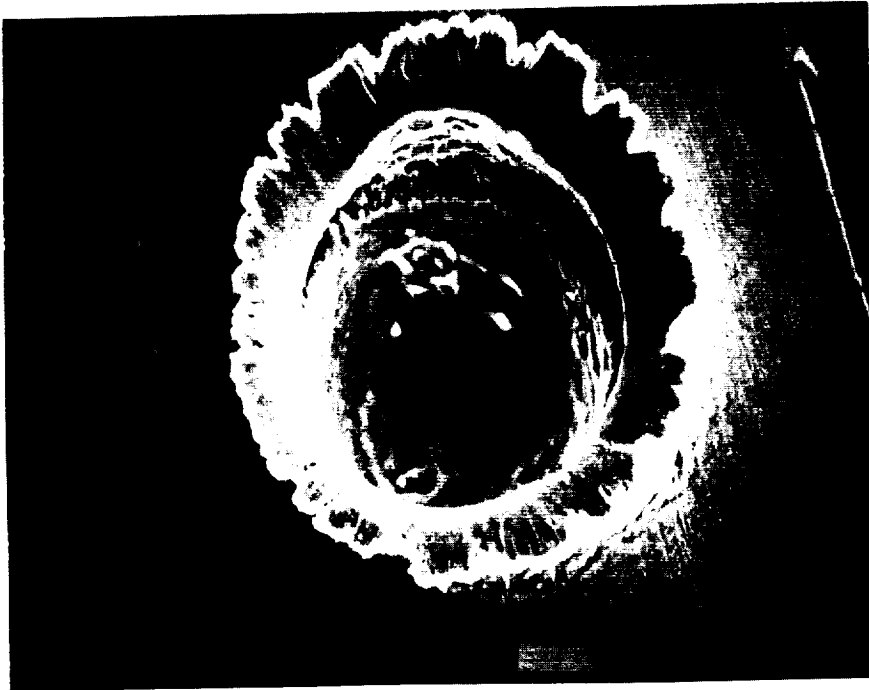


COMPONENT: EOOJ
FEATURE: 262
CORE: LD-214
DIAMETER: 30 μ m
ORIGIN: Man-made

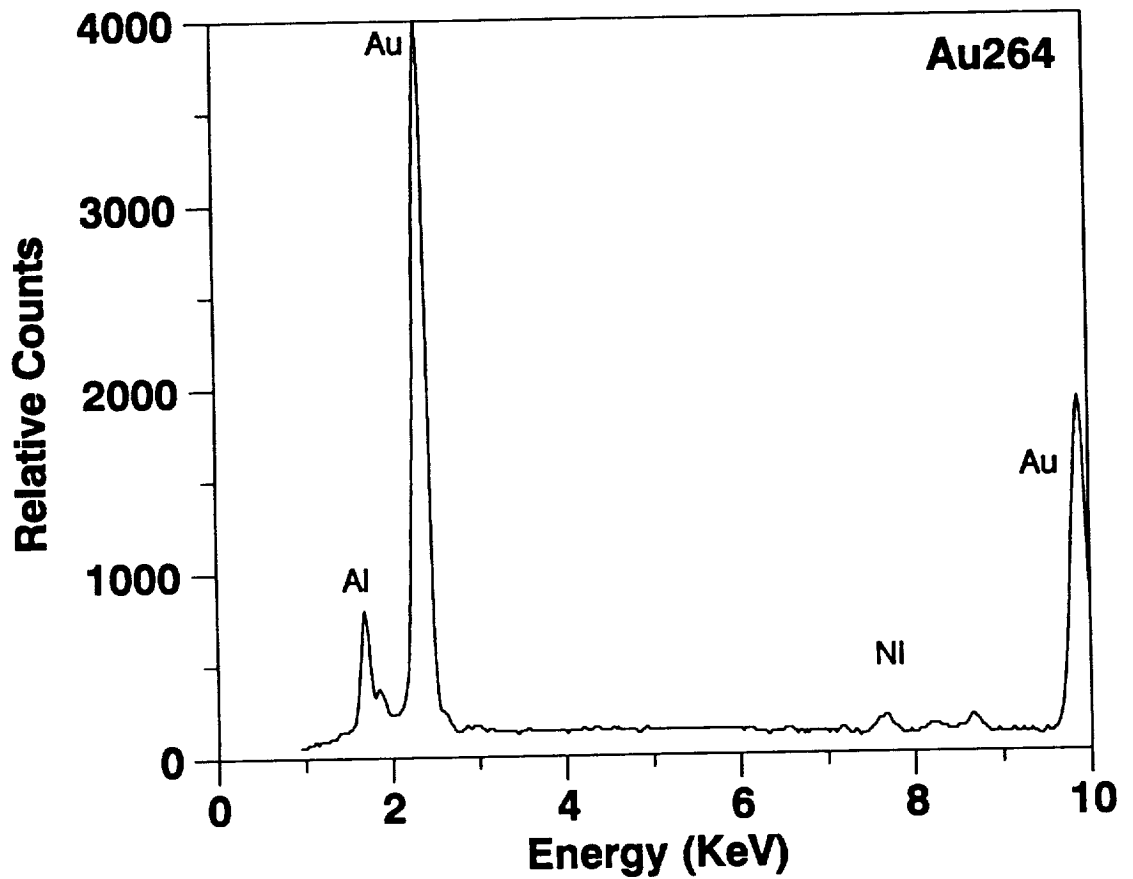


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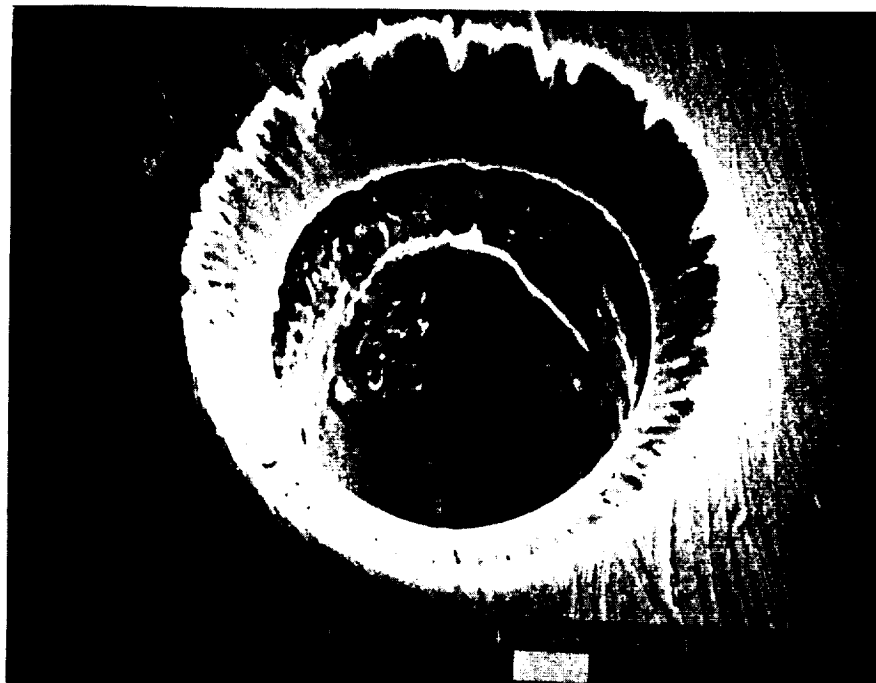


COMPONENT: EOOJ
FEATURE: 264
CORE: LD-216
DIAMETER: 30 μ m
ORIGIN: Man-made



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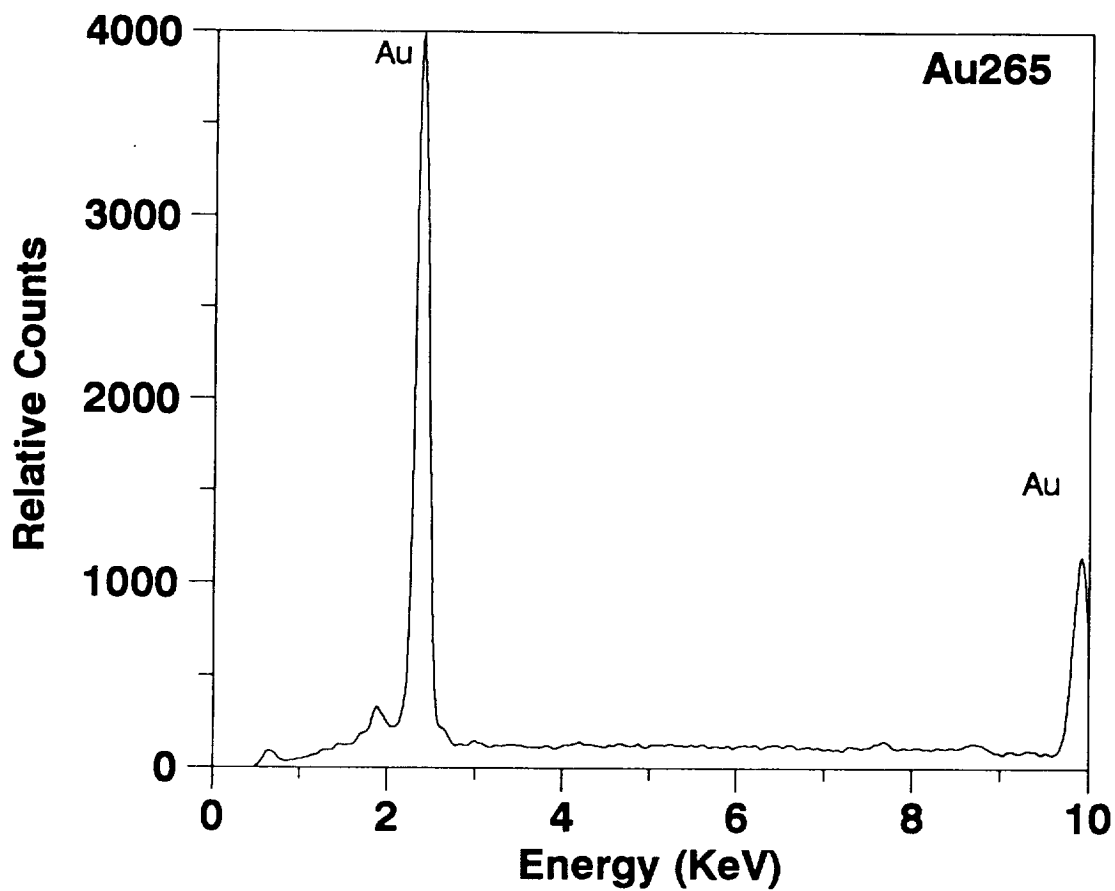
COMPONENT: EOOJ

FEATURE: 265

CORE: LD-218

DIAMETER: 25 μ m

ORIGIN: Unknown



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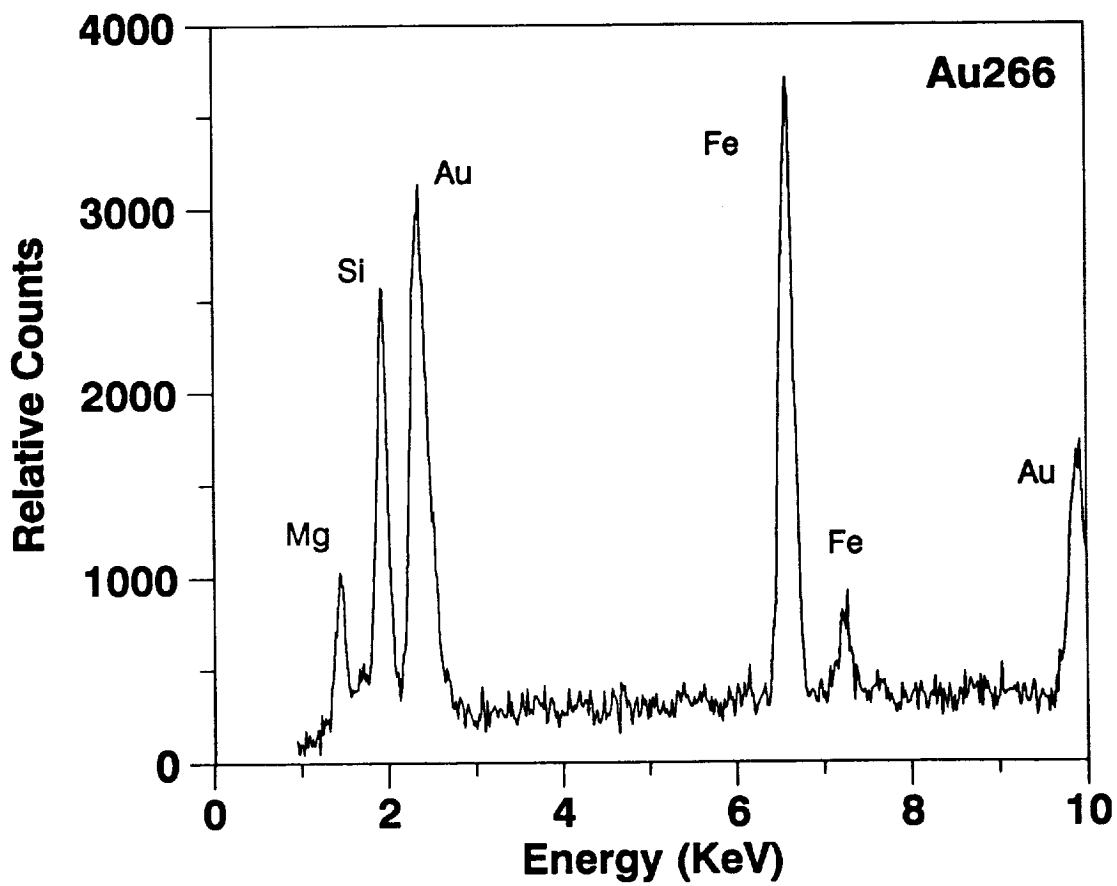
COMPONENT: EOOJ

FEATURE: 266

CORE: LD-217

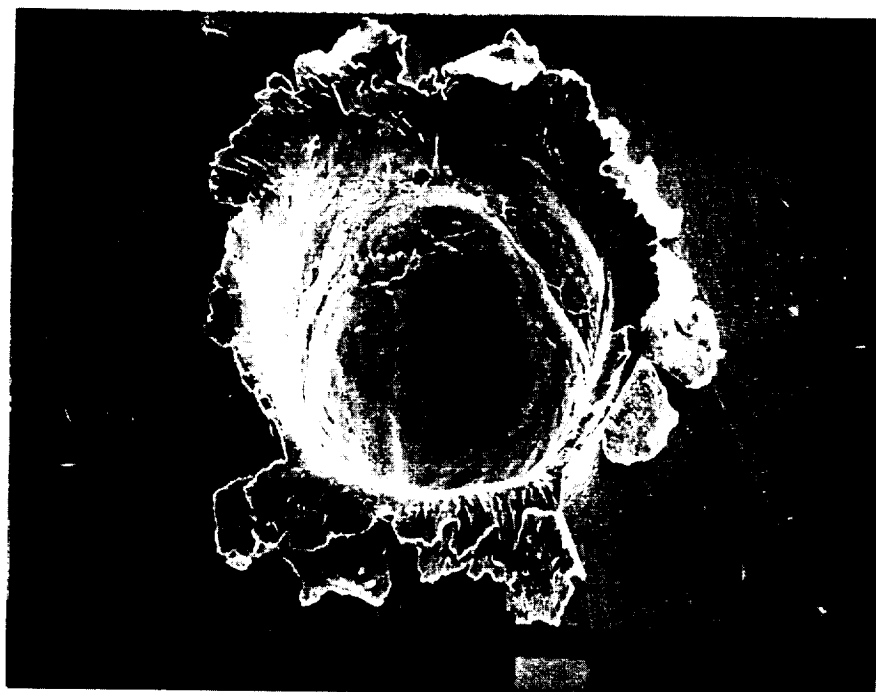
DIAMETER: 460 μm

ORIGIN: Natural

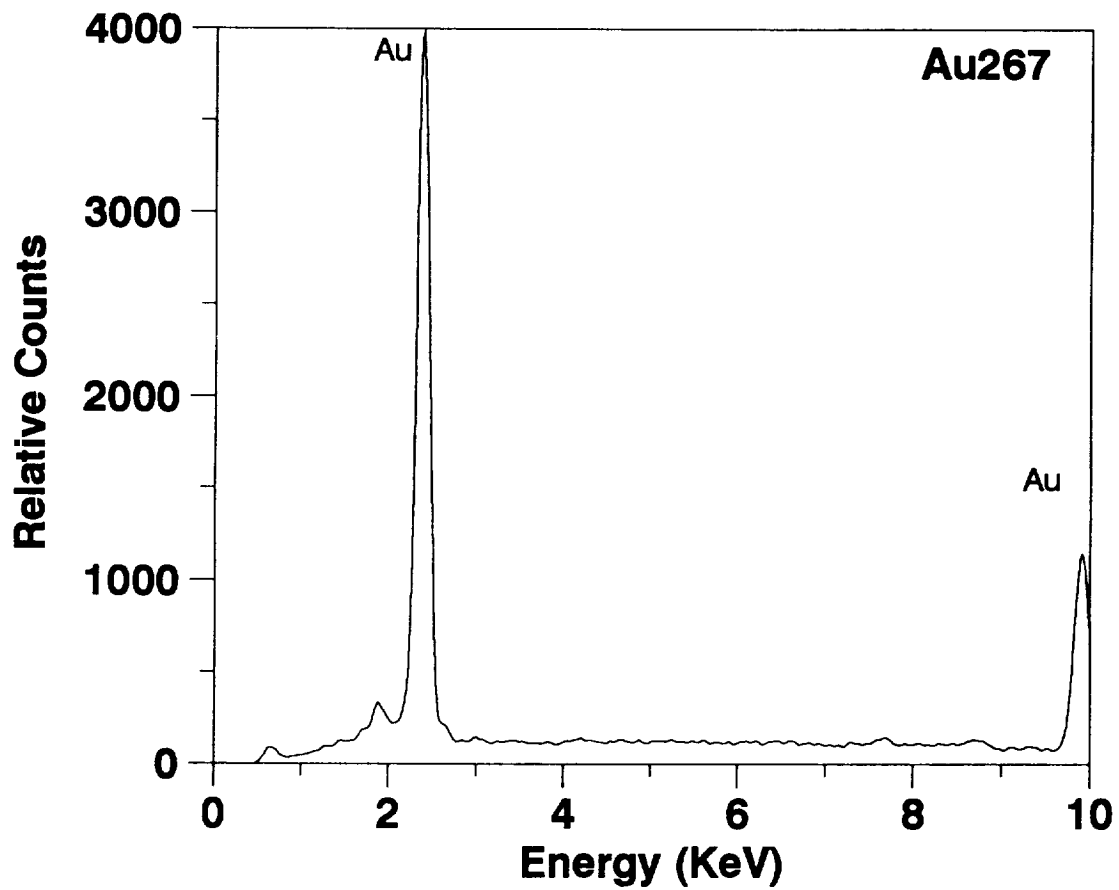


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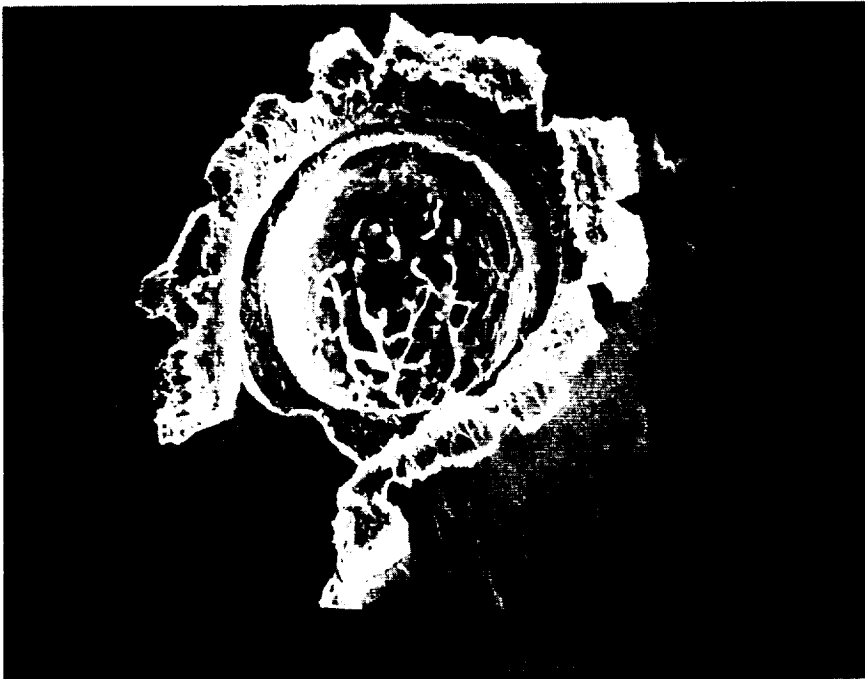


COMPONENT: EOOJ
FEATURE: 267
CORE: LD-219
DIAMETER: 115 μm
ORIGIN: Unknown

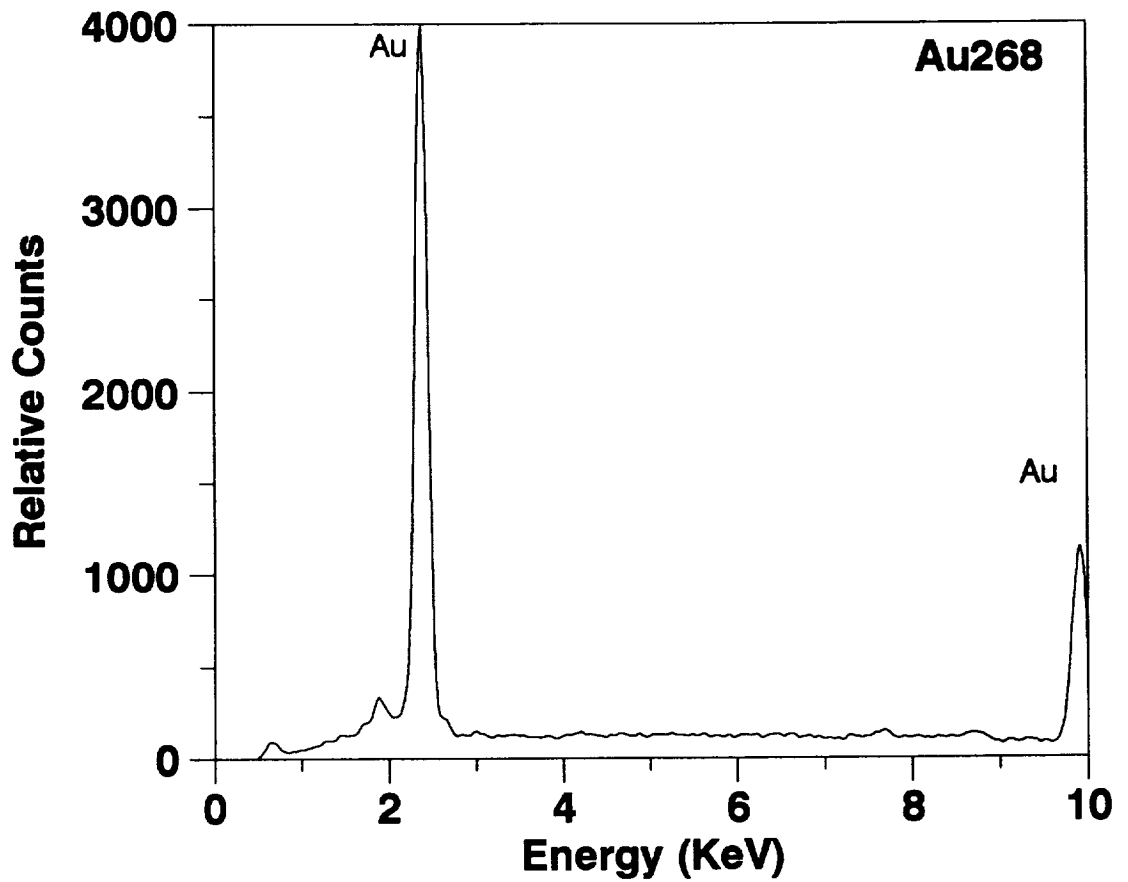


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COMPONENT: EOOJ
FEATURE: 268
CORE: LD-220
DIAMETER: 40 μ m
ORIGIN: Unknown

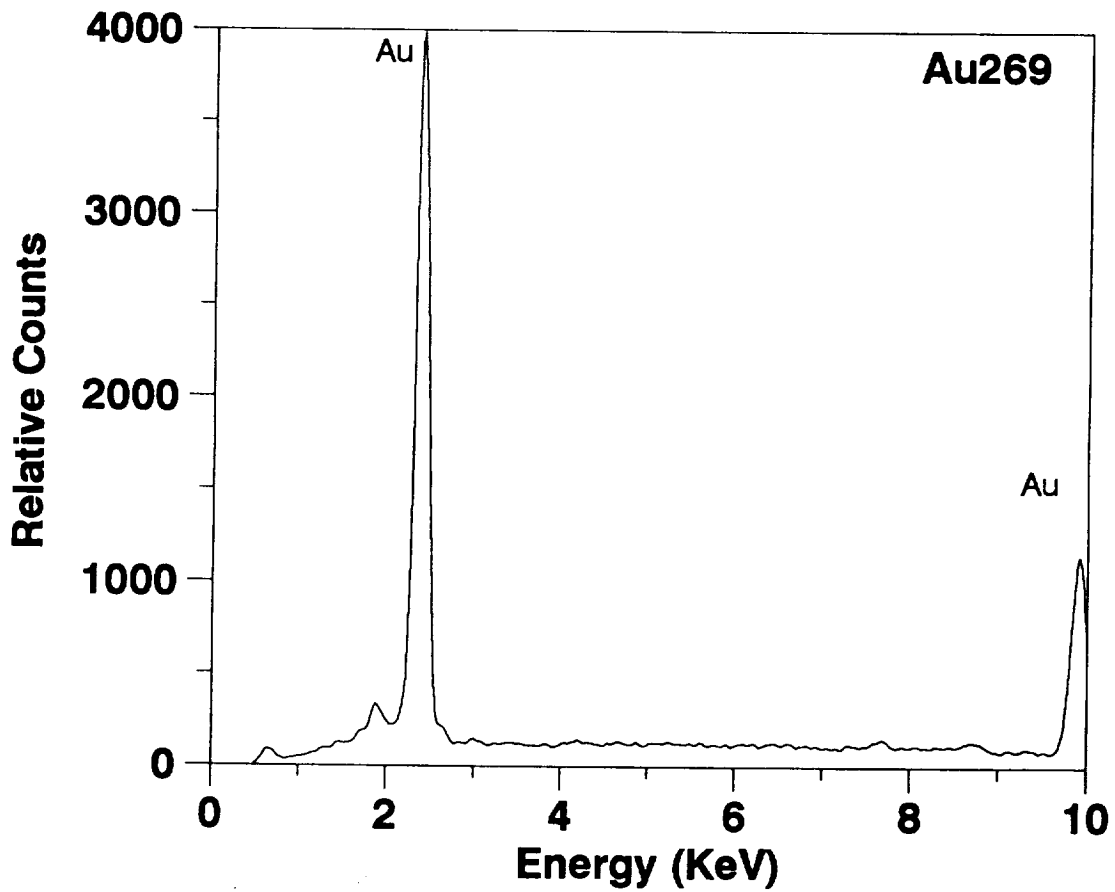


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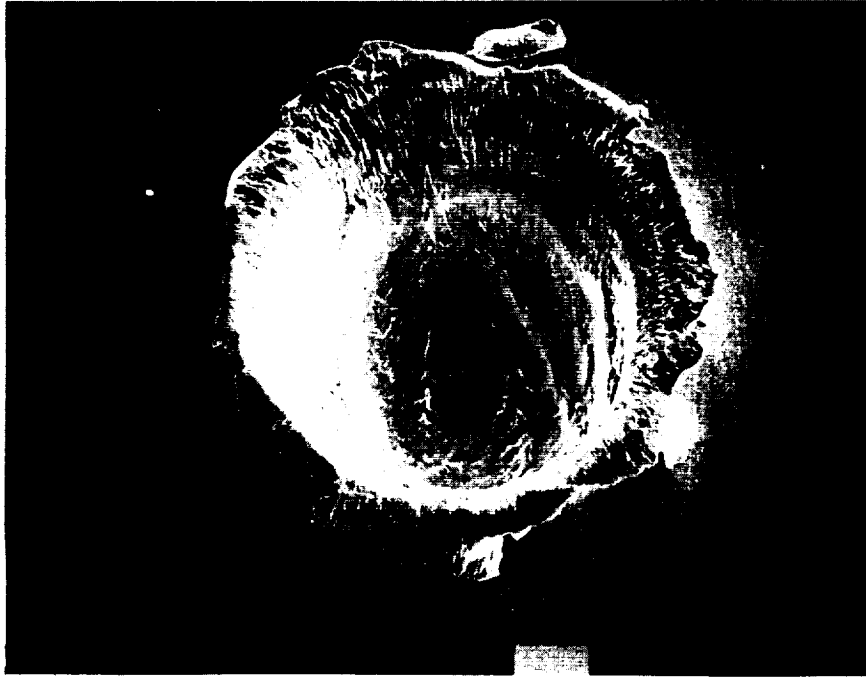


COMPONENT: EOOJ
FEATURE: 269
CORE: LD-221
DIAMETER: 45 μm
ORIGIN: Unknown

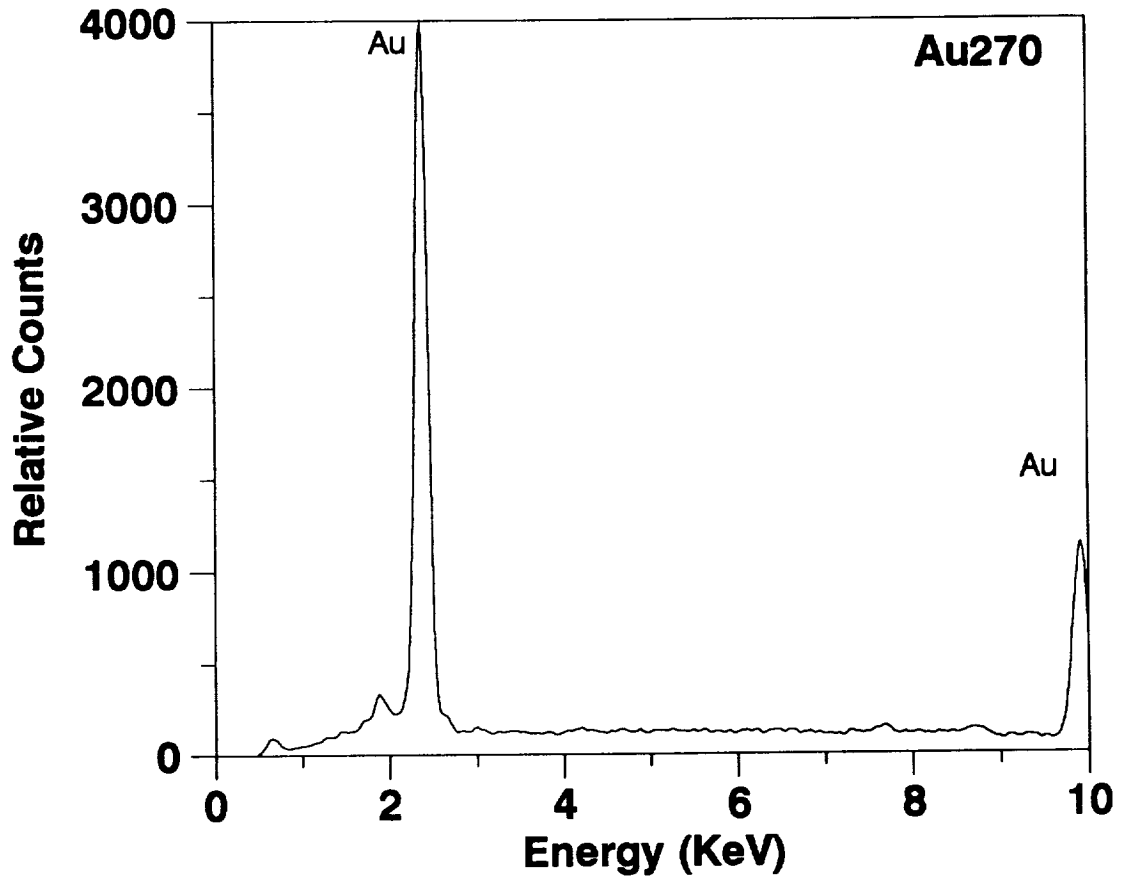


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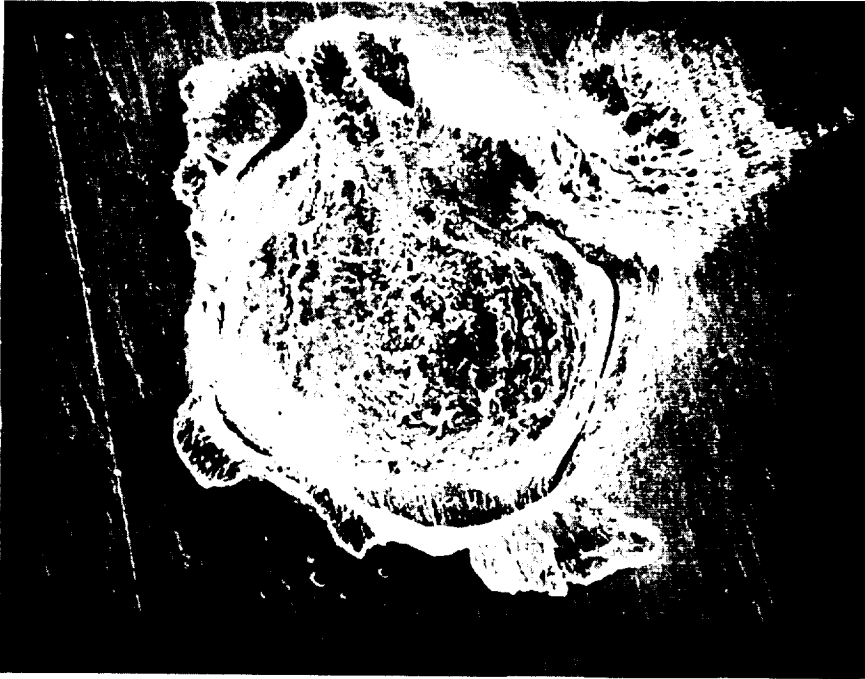


COMPONENT: EOOJ
FEATURE: 270
CORE: LD-222
DIAMETER: 330 μ m
ORIGIN: Unknown

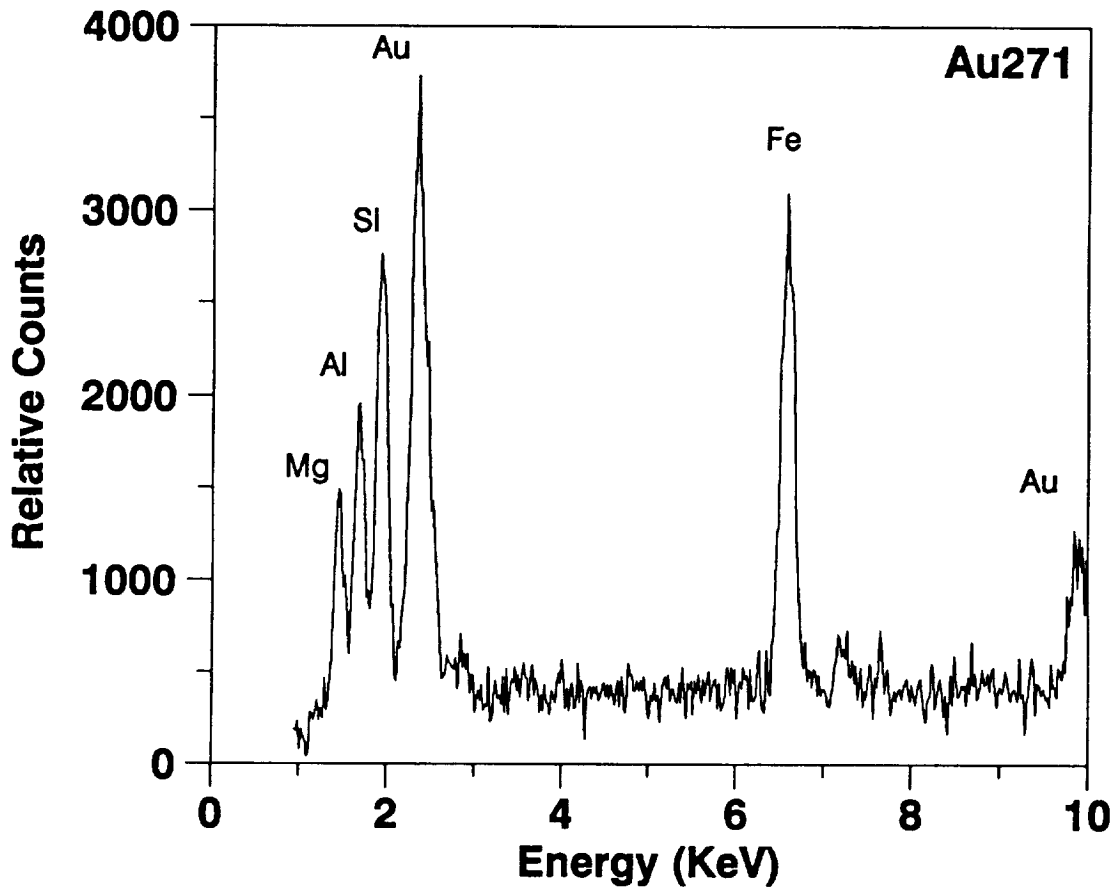


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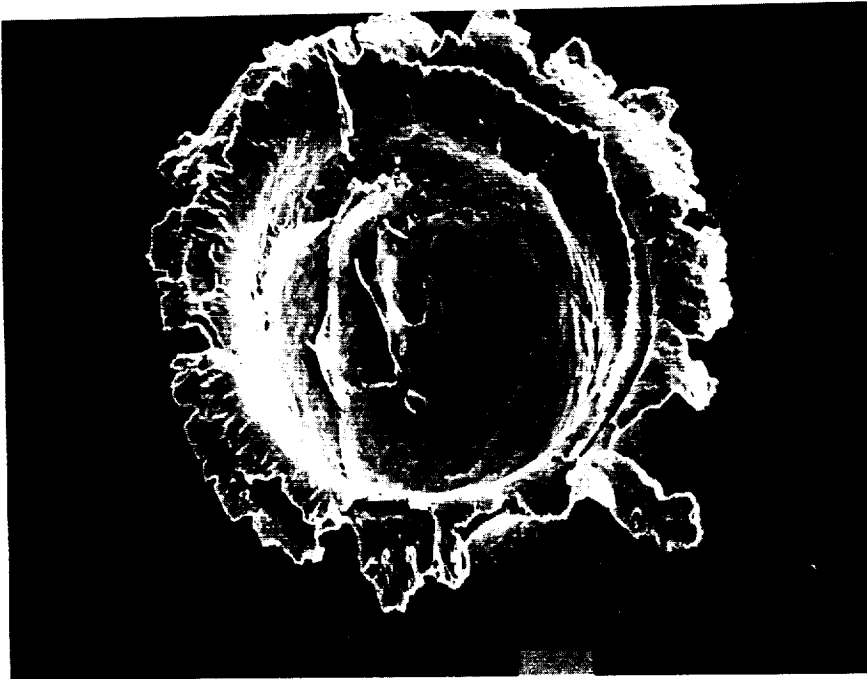


COMPONENT: EOOJ
FEATURE: 271
CORE: LD-233
DIAMETER: 60 μm
ORIGIN: Natural



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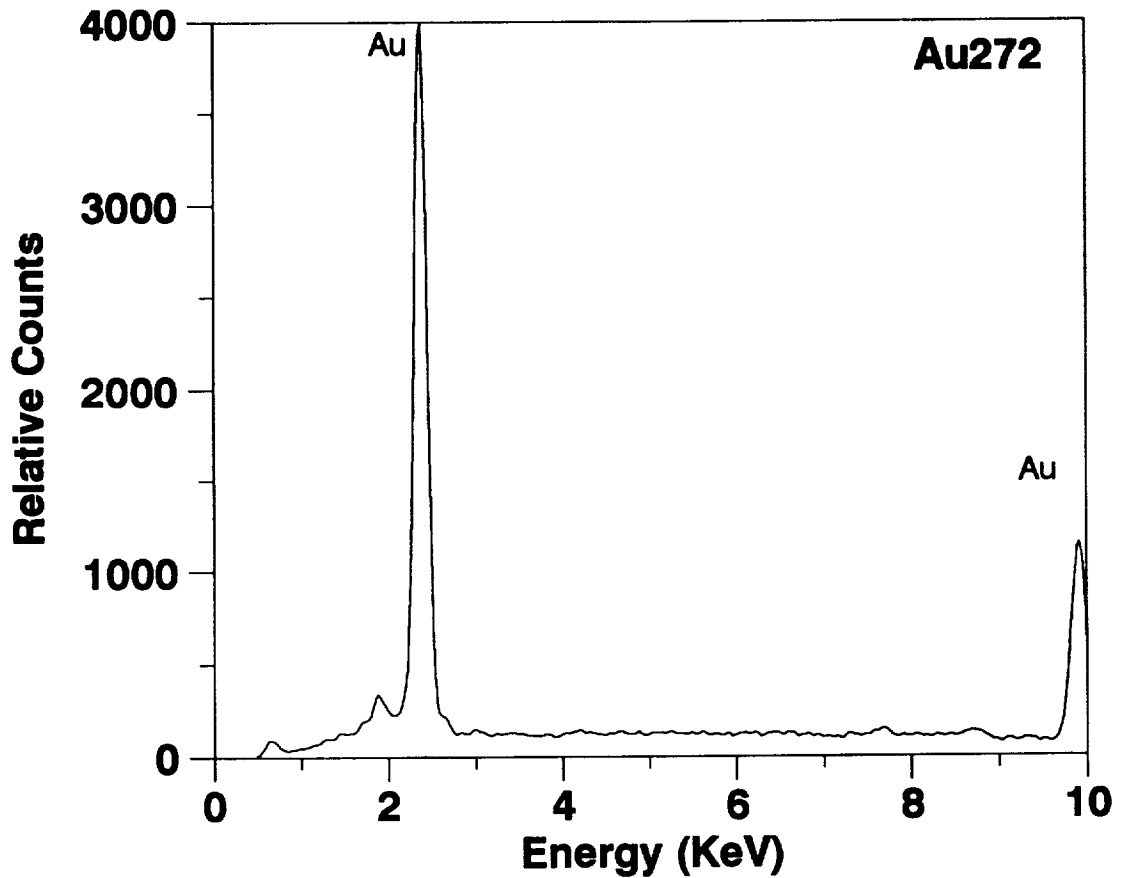
COMPONENT: EOOJ

FEATURE: 272

CORE: LD-224

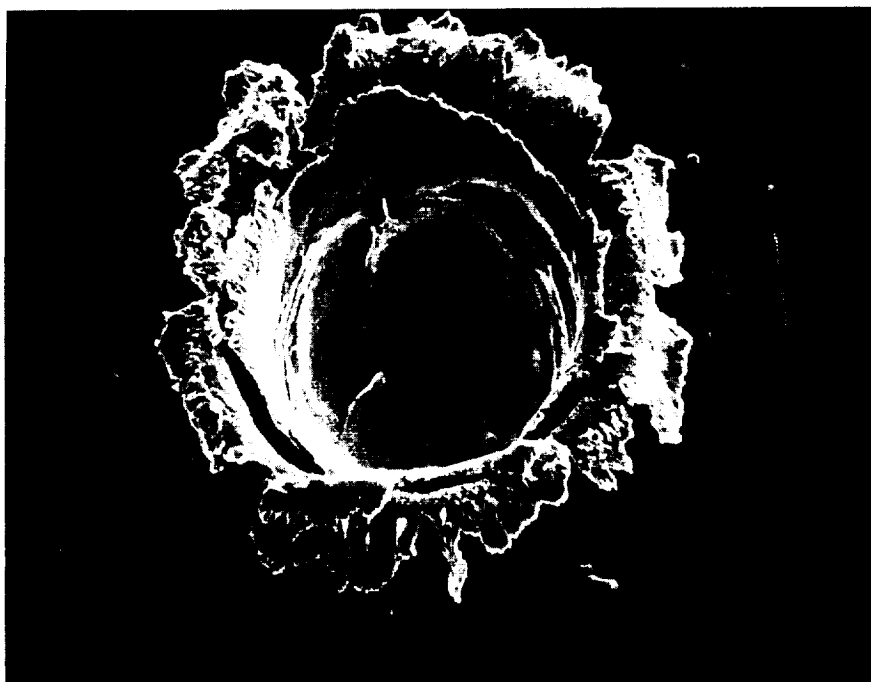
DIAMETER: 65 μ m

ORIGIN: Unknown



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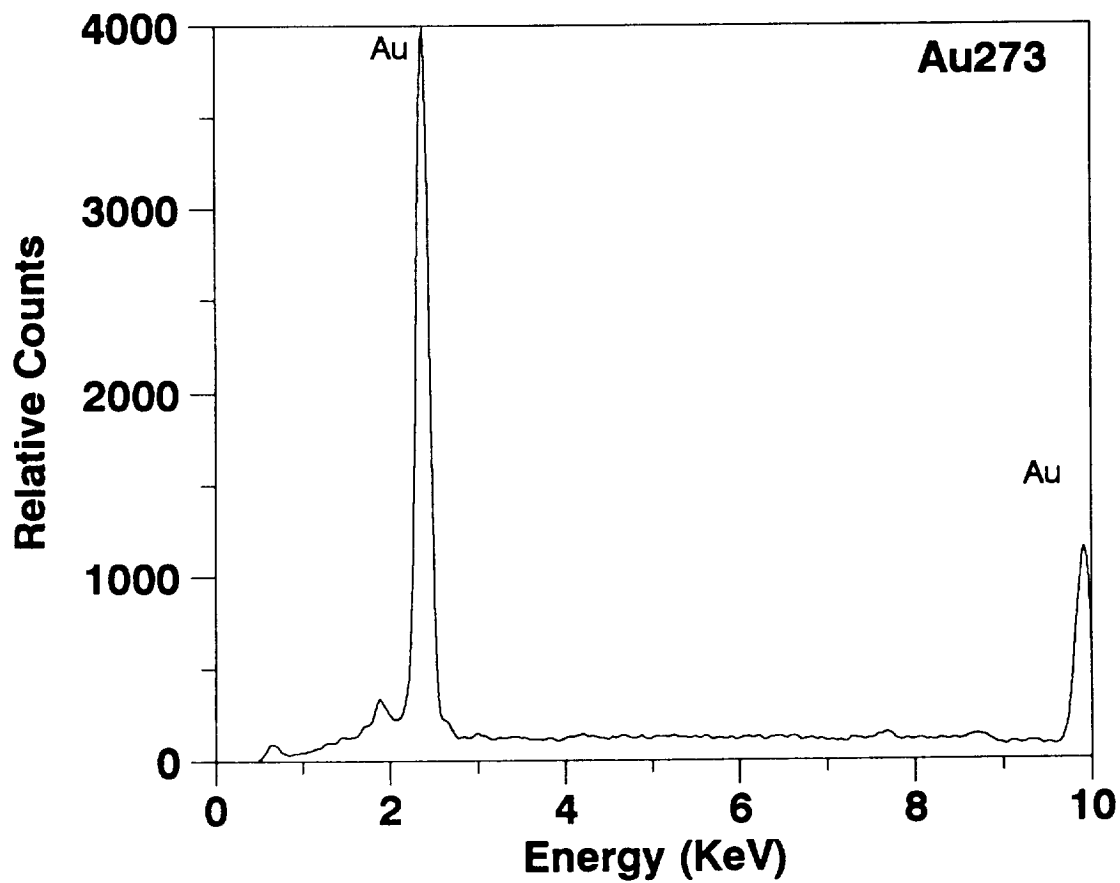
COMPONENT: EOOJ

FEATURE: 273

CORE: LD-225

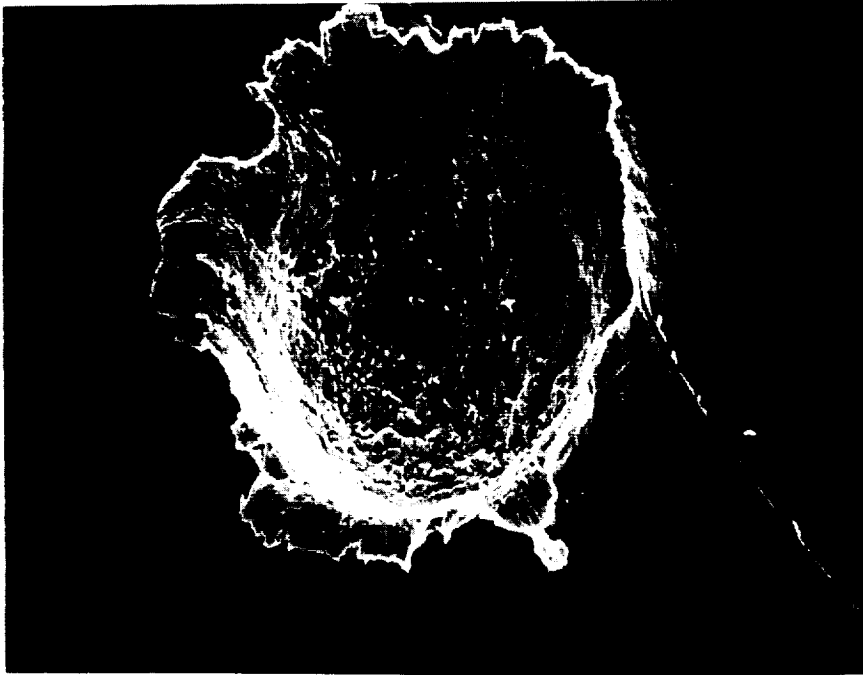
DIAMETER: 55 μm

ORIGIN: Unknown

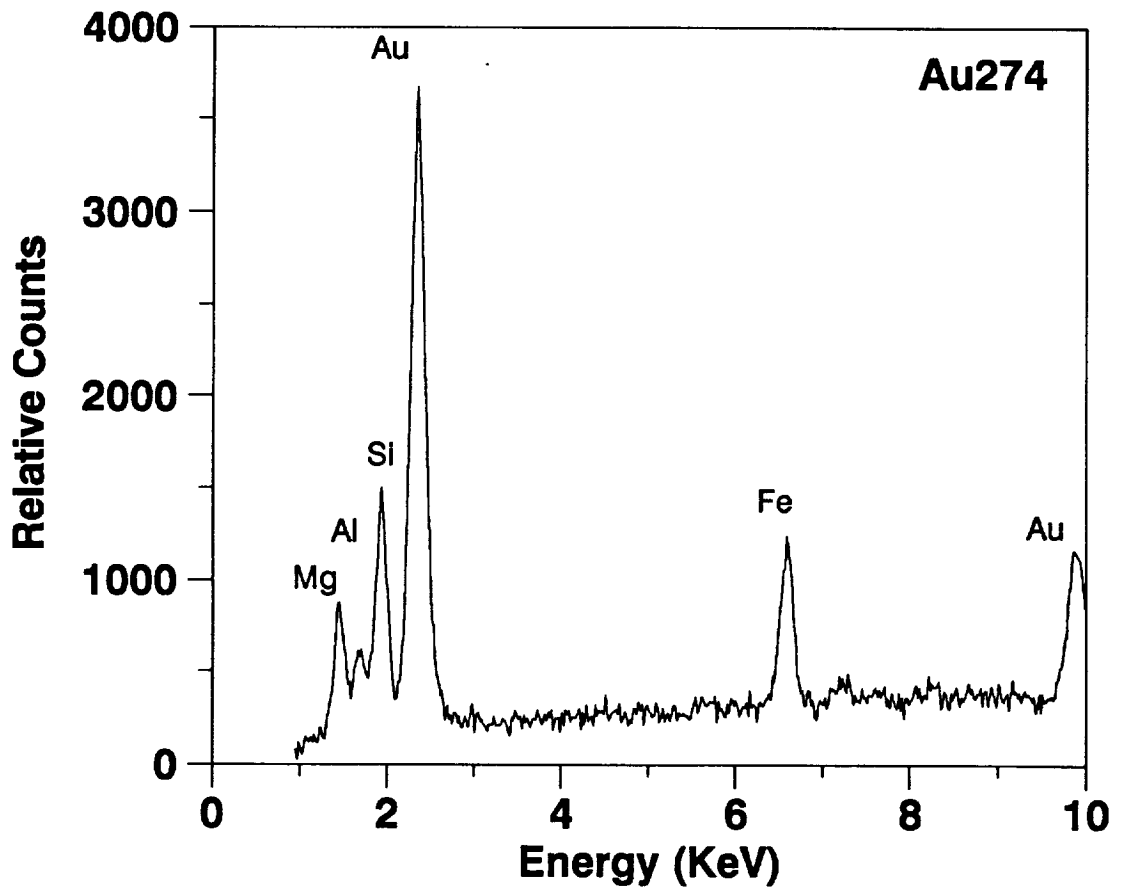


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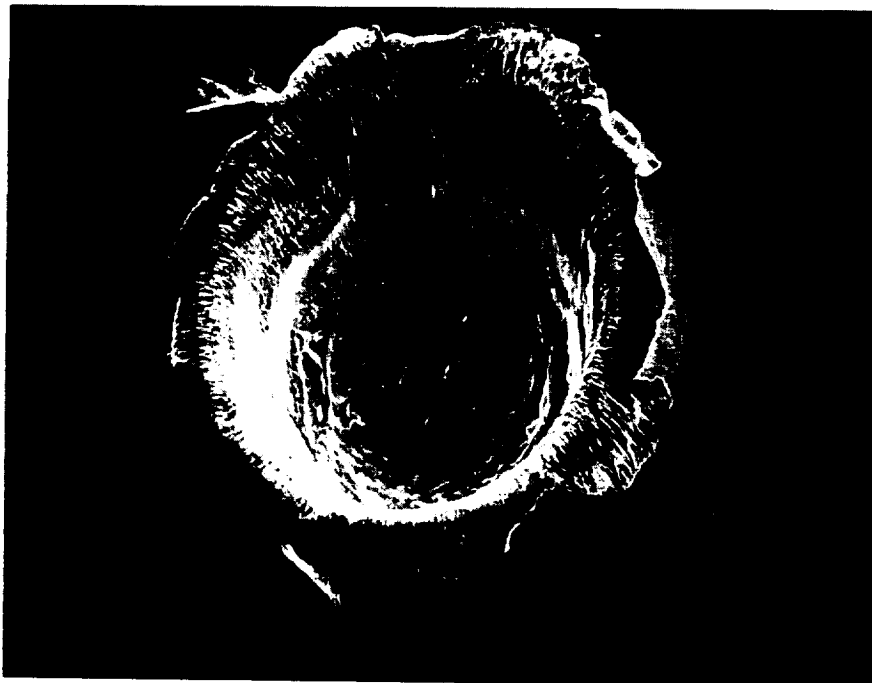


COMPONENT: EOOK
FEATURE: 274
CORE: LD-259
DIAMETER: 45 μ m
ORIGIN: Natural

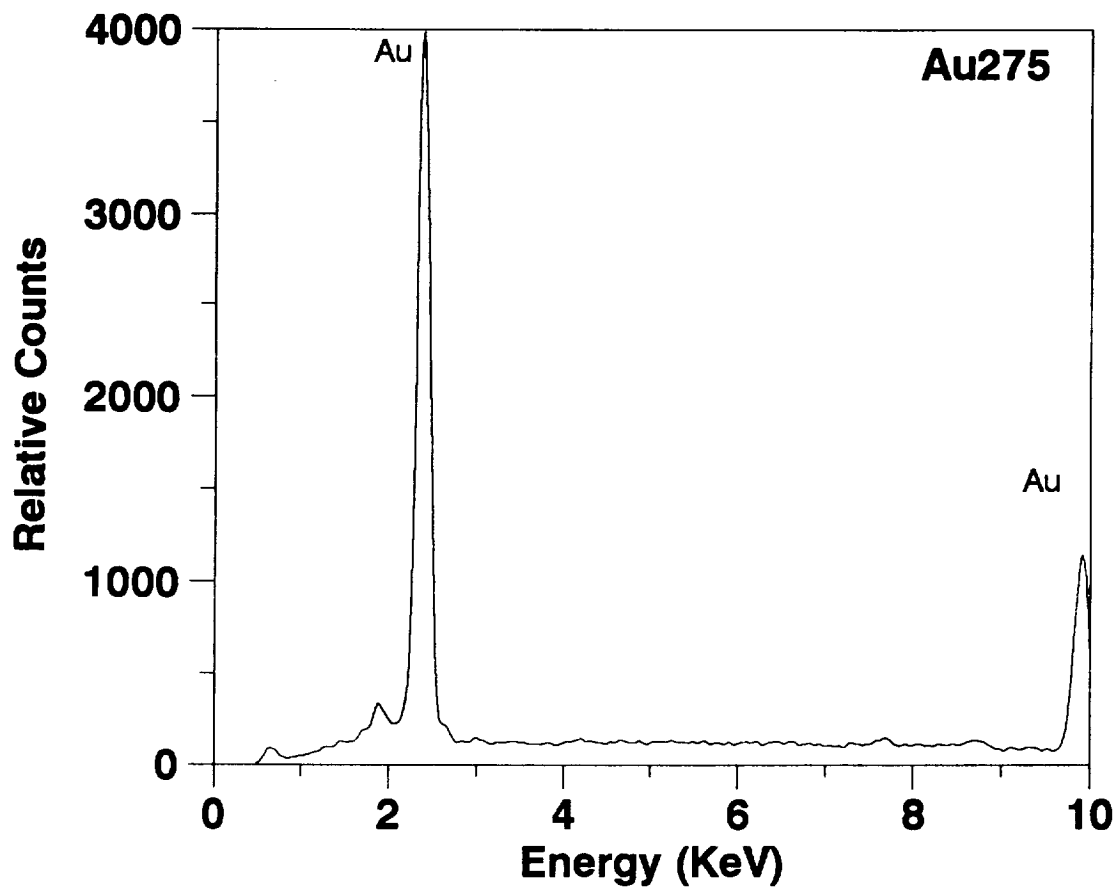


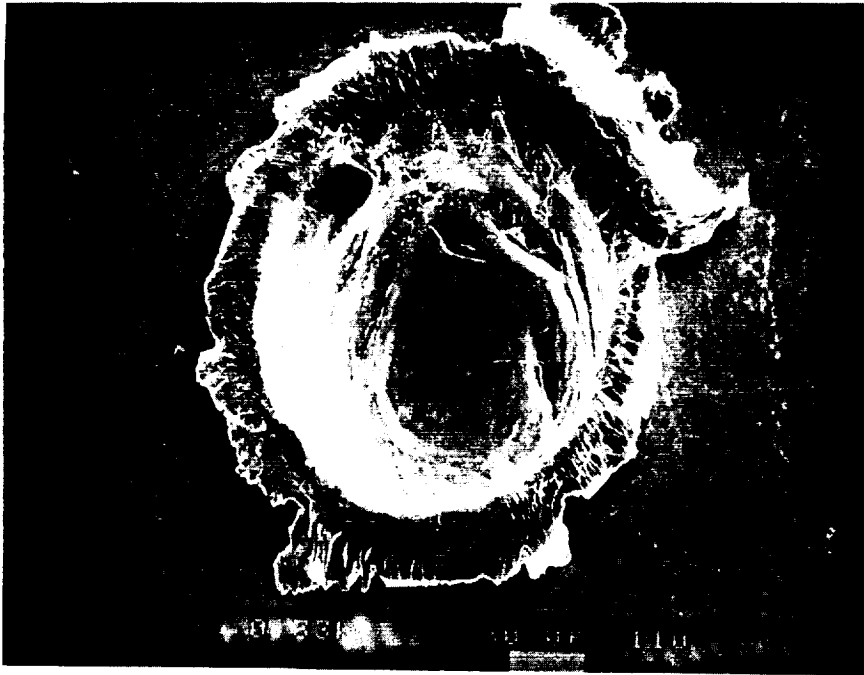
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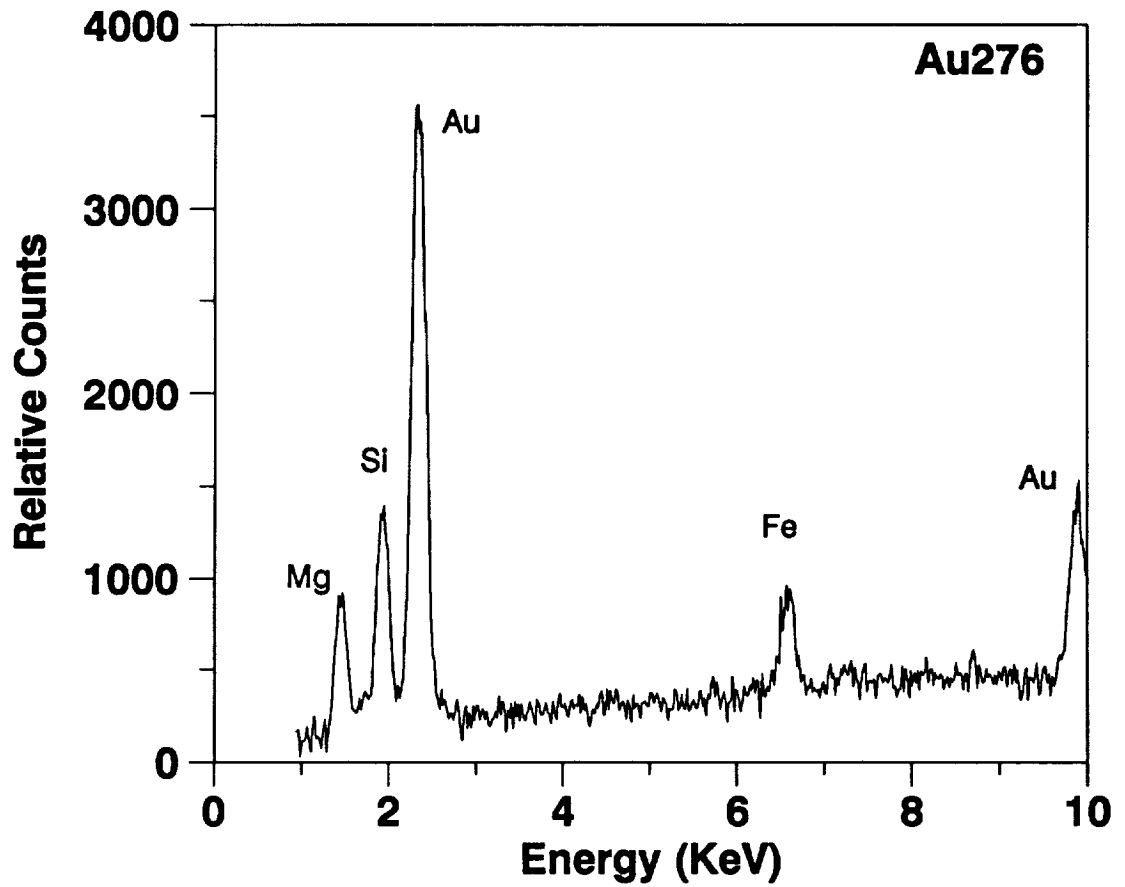


COMPONENT: EOOK
FEATURE: 275
CORE: LD-260
DIAMETER: 485 μ m
ORIGIN: Unknown



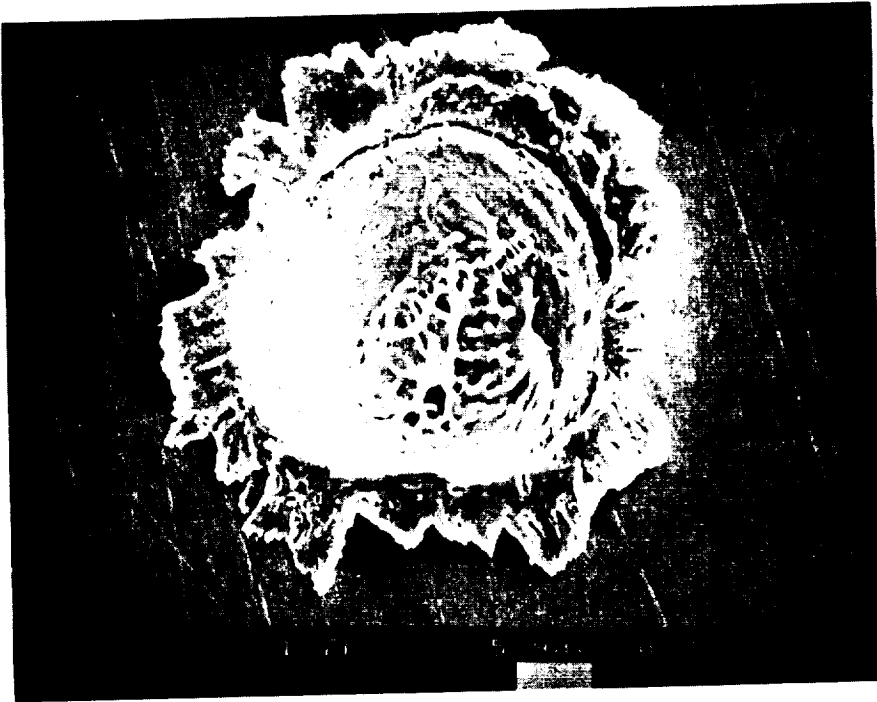


COMPONENT: EOOK
FEATURE: 276
CORE: LD-261
DIAMETER: 170 μm
ORIGIN: Natural

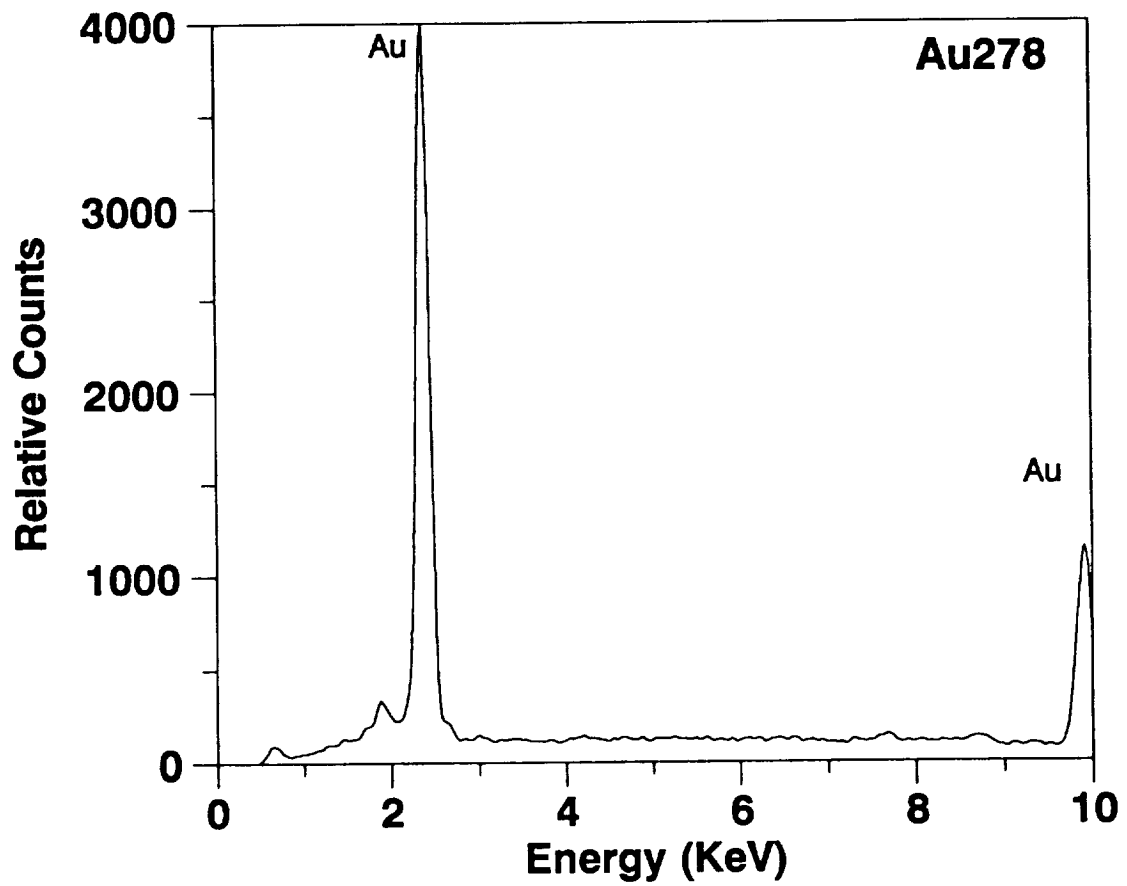


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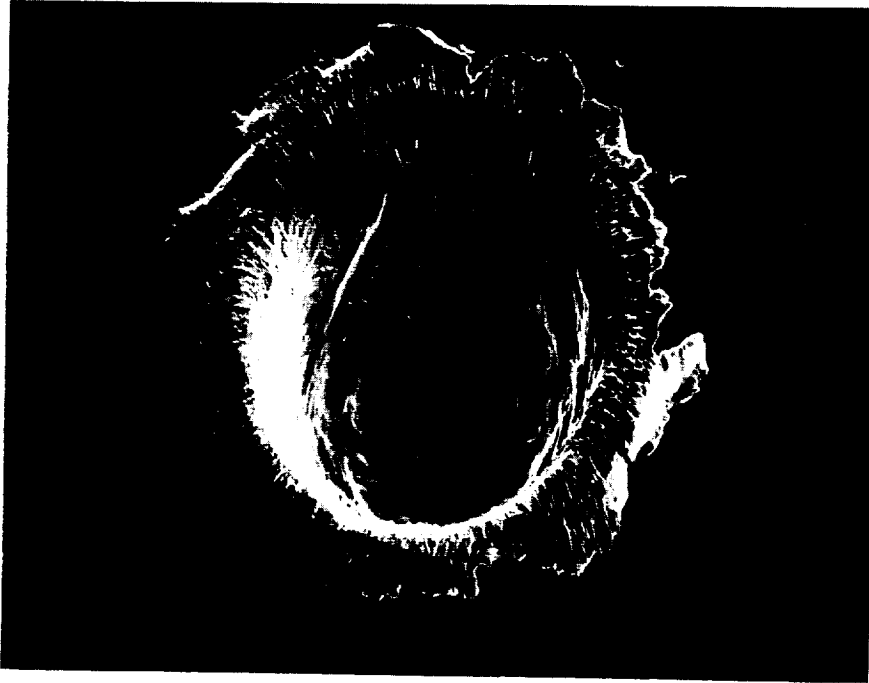


COMPONENT: EOOK
FEATURE: 278
CORE: LD-232
DIAMETER: 30 μ m
ORIGIN: Unknown

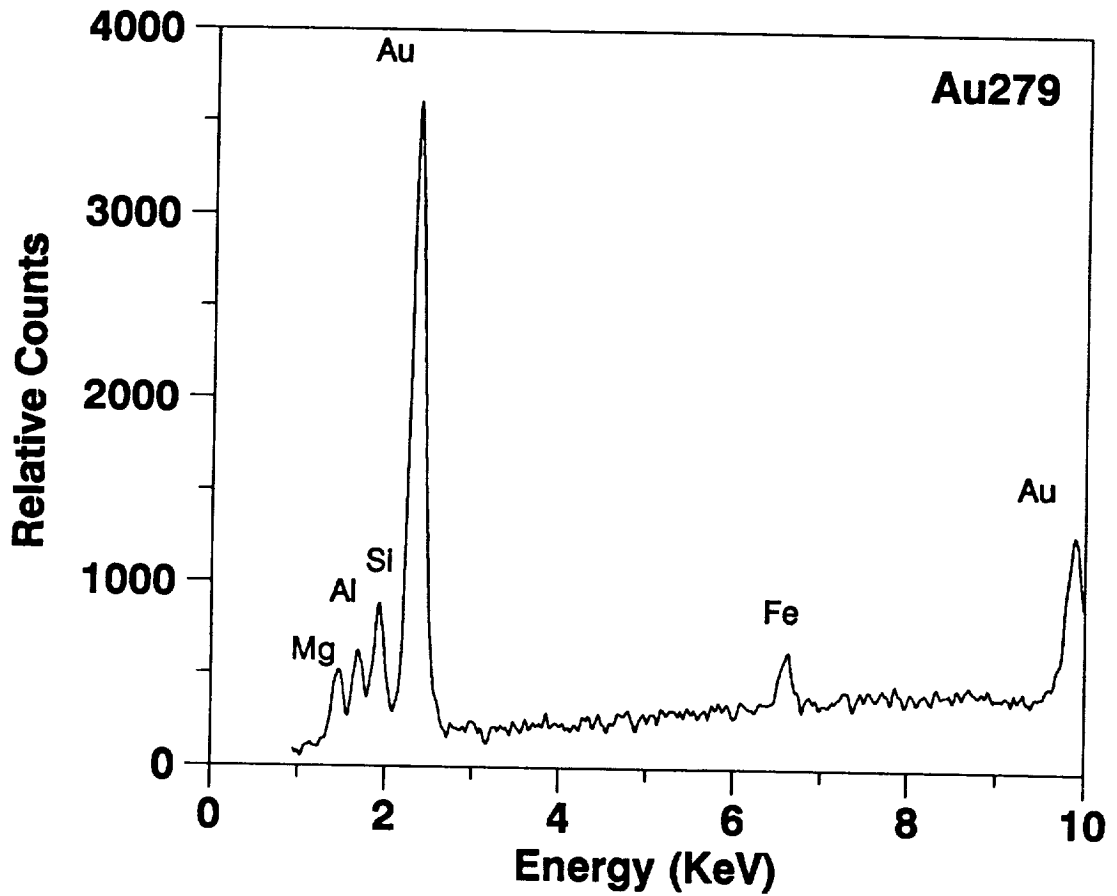


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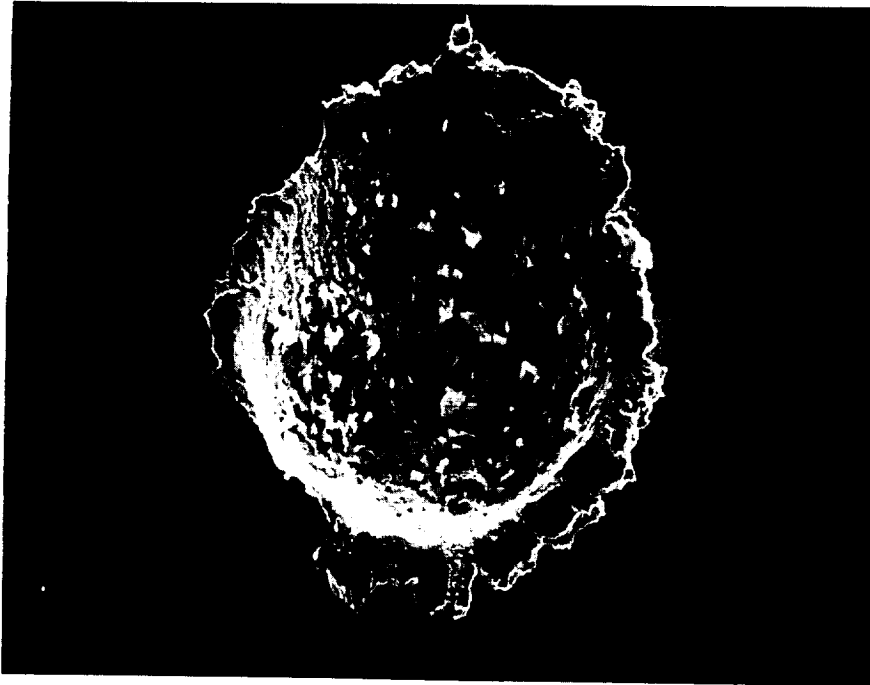


COMPONENT: EOOK
FEATURE: 279
CORE: LD-233
DIAMETER: 220 μm
ORIGIN: Natural

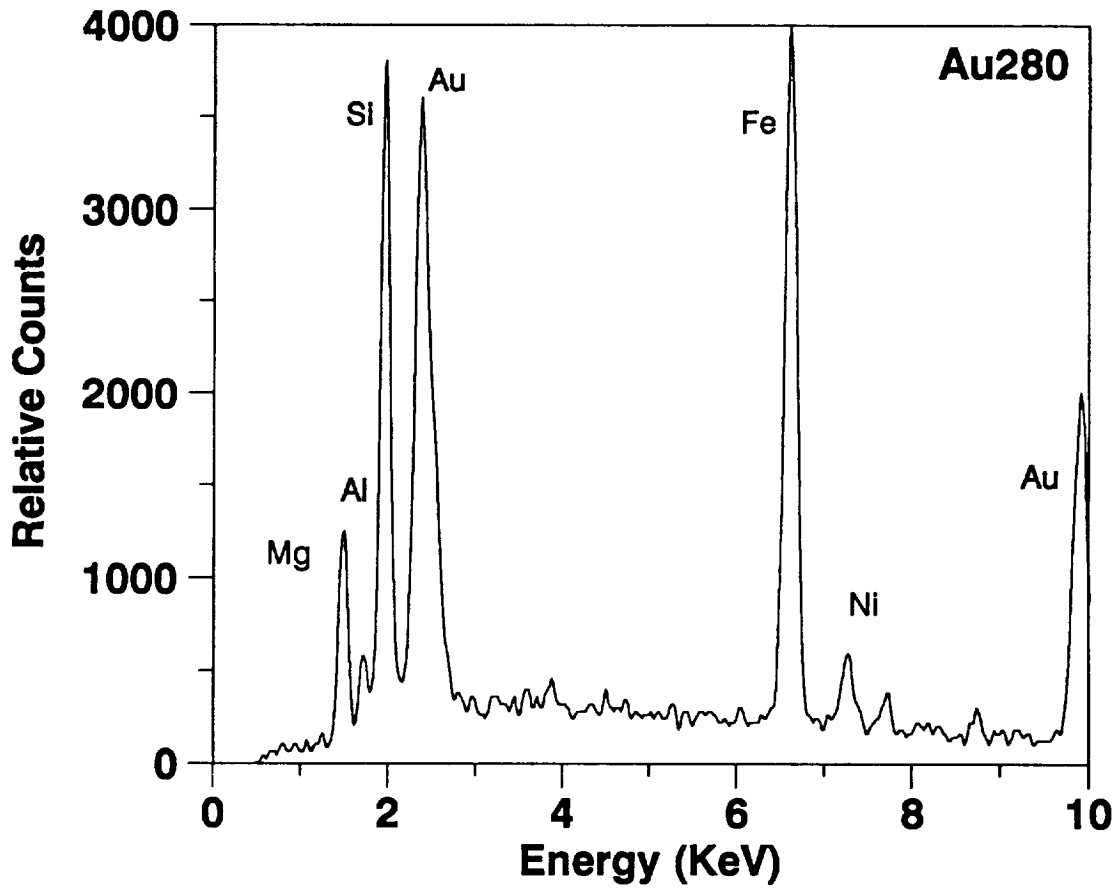


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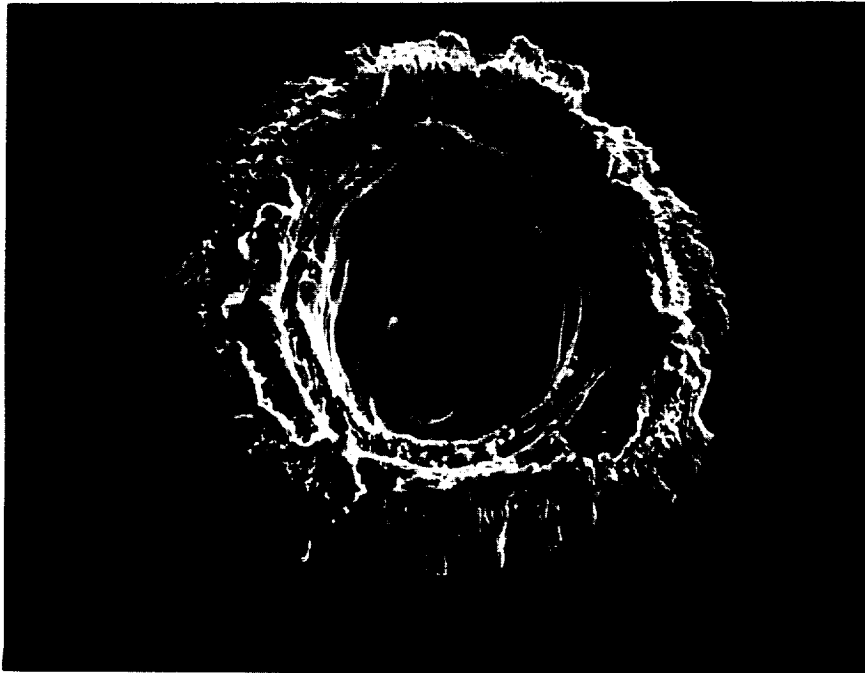


COMPONENT: EOOK
FEATURE: 280
CORE: LD-234
DIAMETER: 160 μm
ORIGIN: Natural

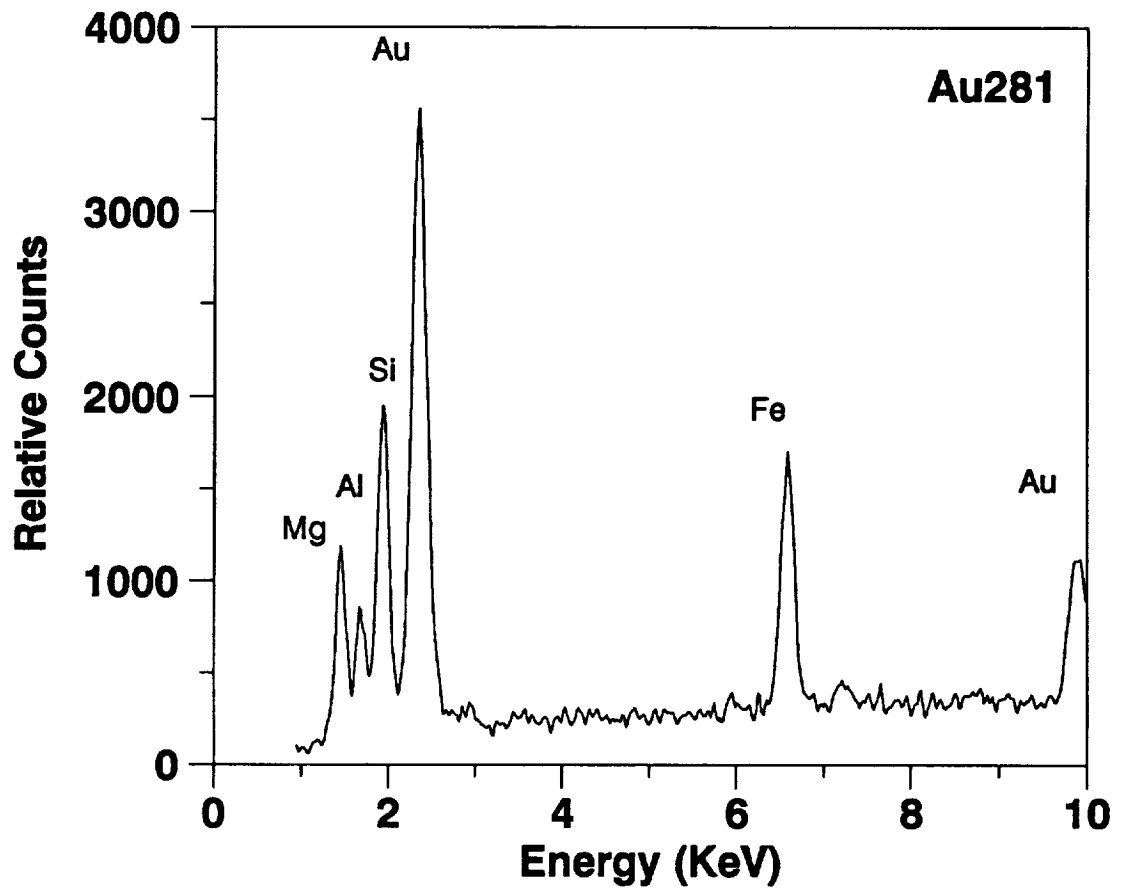


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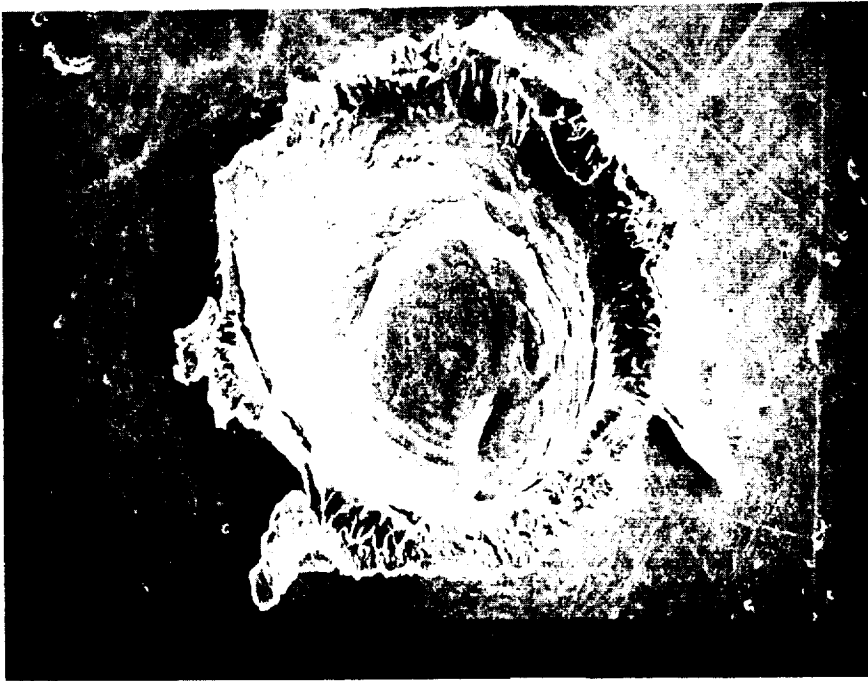


COMPONENT: EOOK
FEATURE: 281
CORE: LD-235
DIAMETER: 40 μ m
ORIGIN: Natural

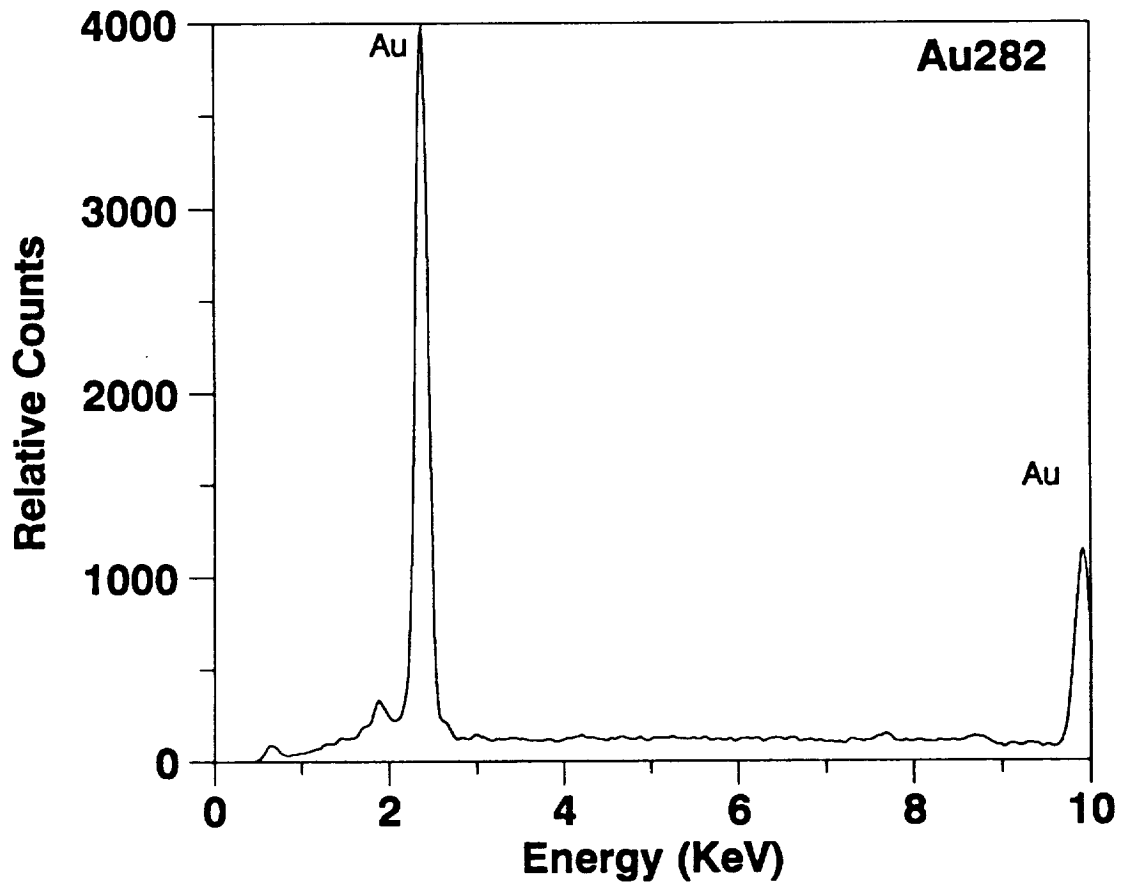


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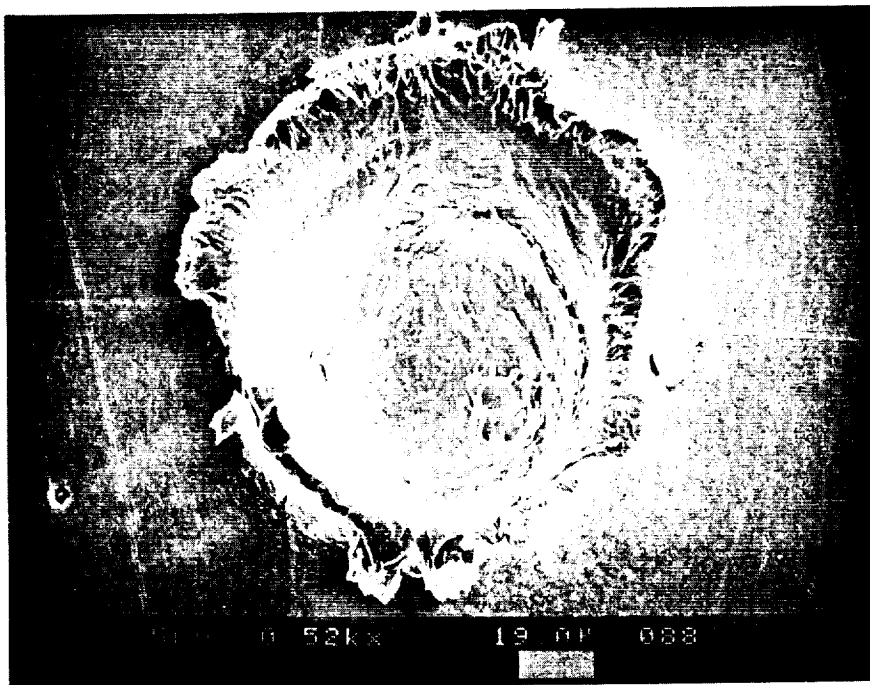


COMPONENT: EOOK
FEATURE: 282
CORE: LD-236
DIAMETER: 75 μm
ORIGIN: Unknown



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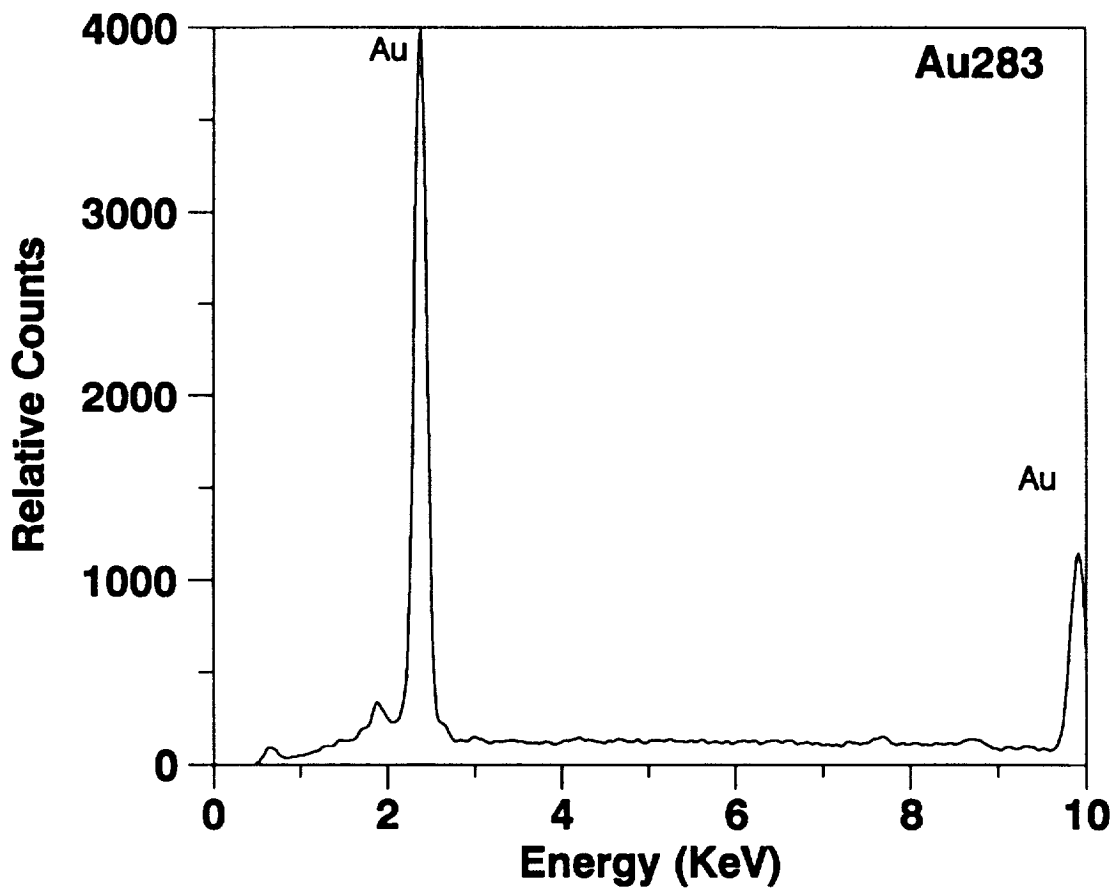
COMPONENT: EOOK

FEATURE: 283

CORE: LD-237

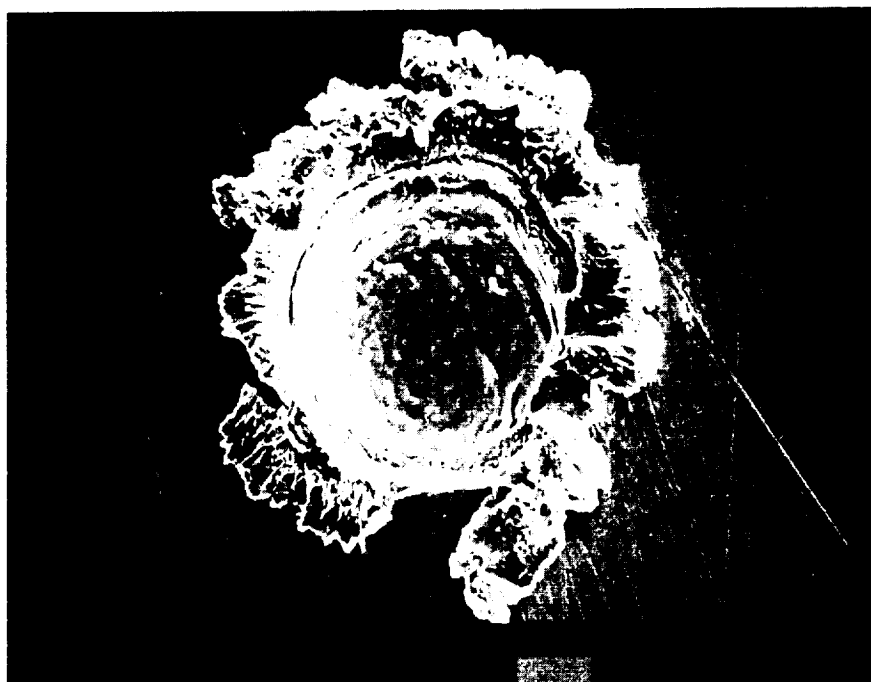
DIAMETER: 90 μ m

ORIGIN: Unknown



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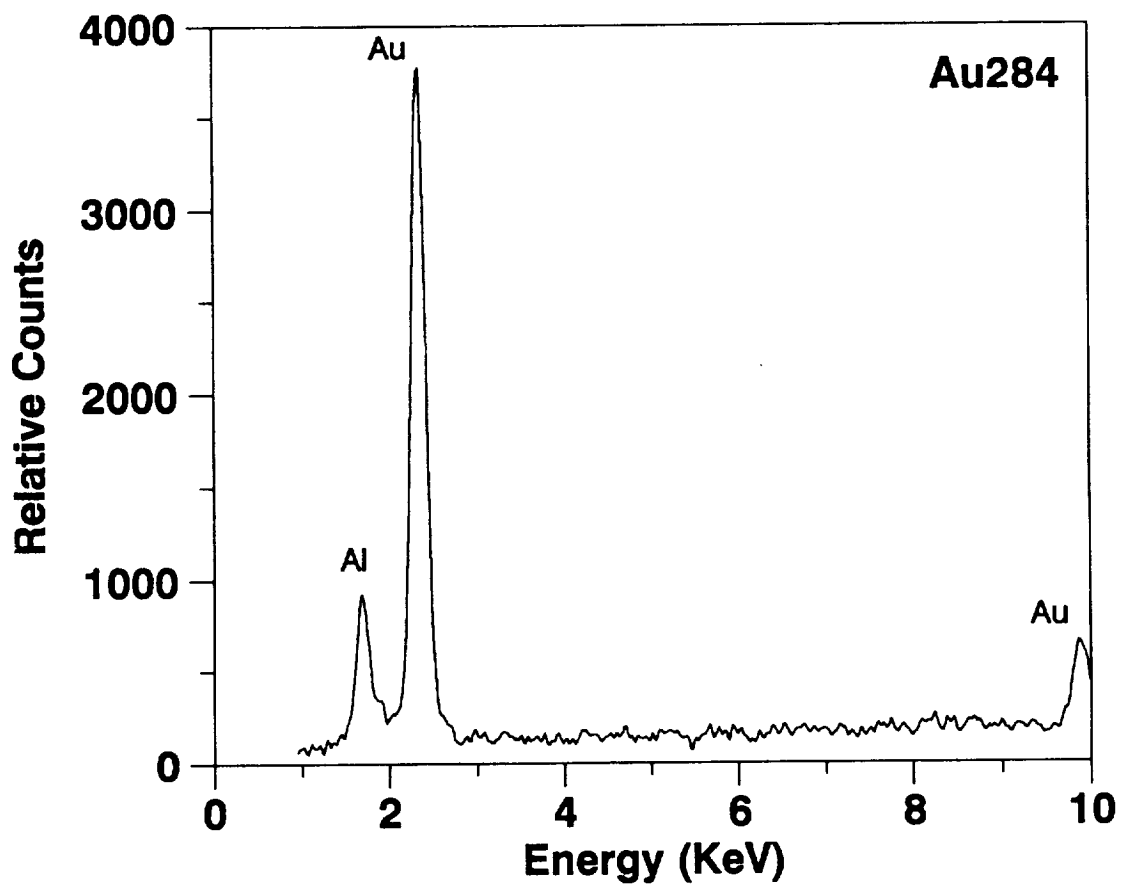
COMPONENT: EOOK

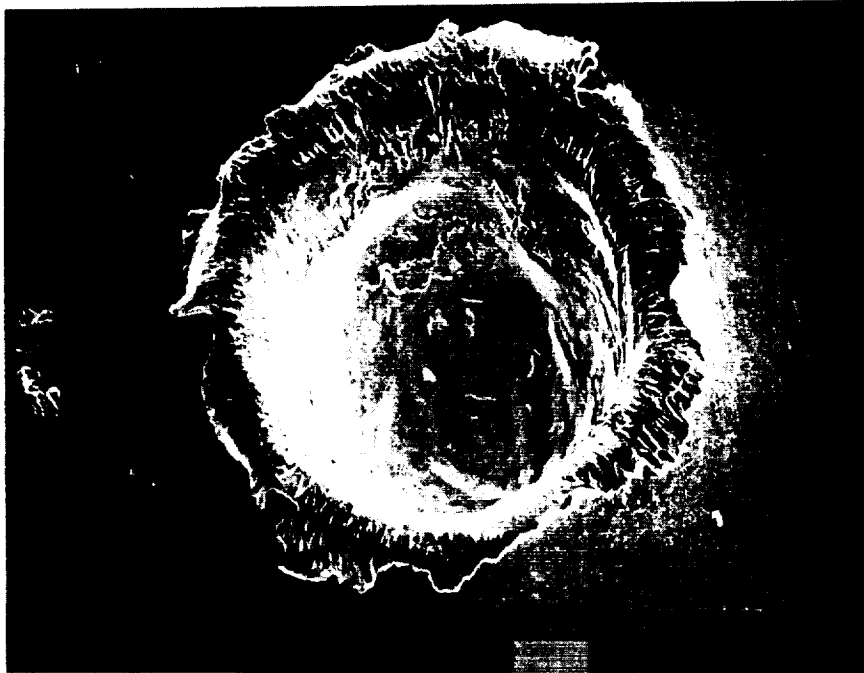
FEATURE: 284

CORE: LD-238

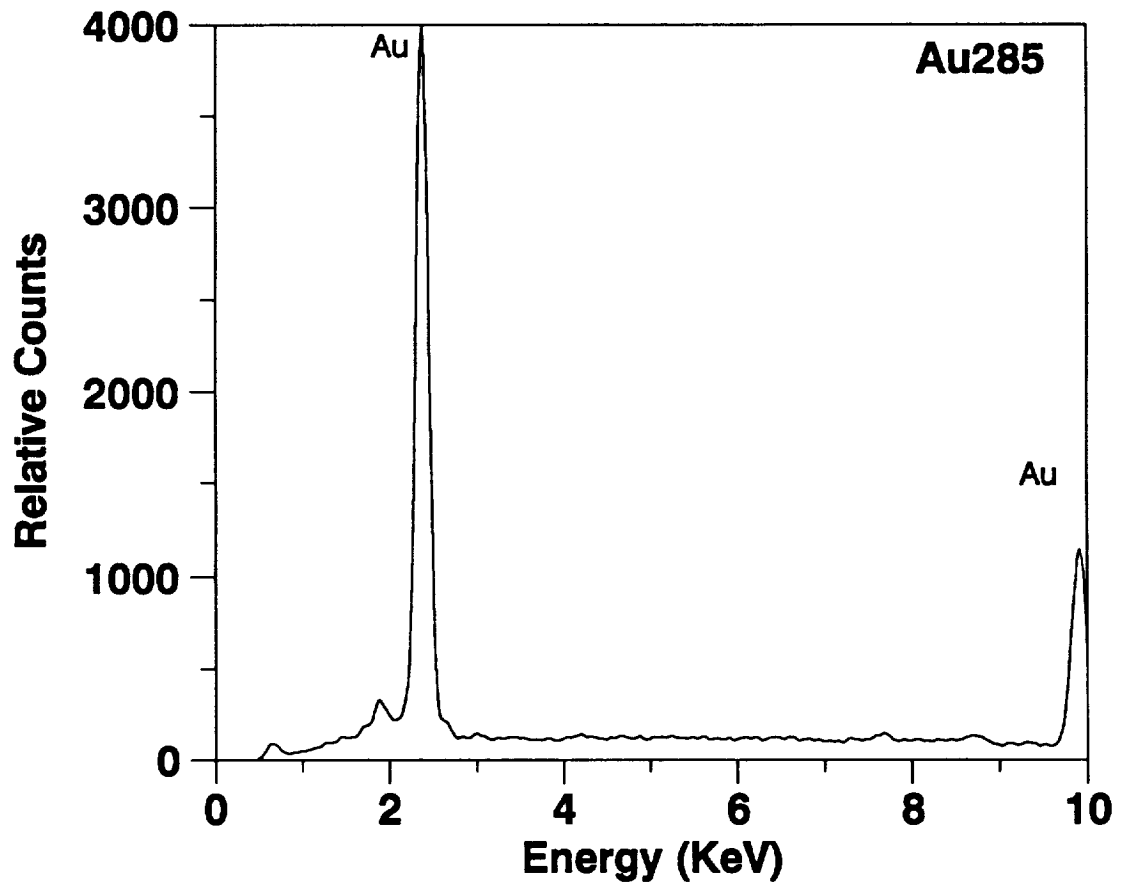
DIAMETER: 45 μ m

ORIGIN: Man-made



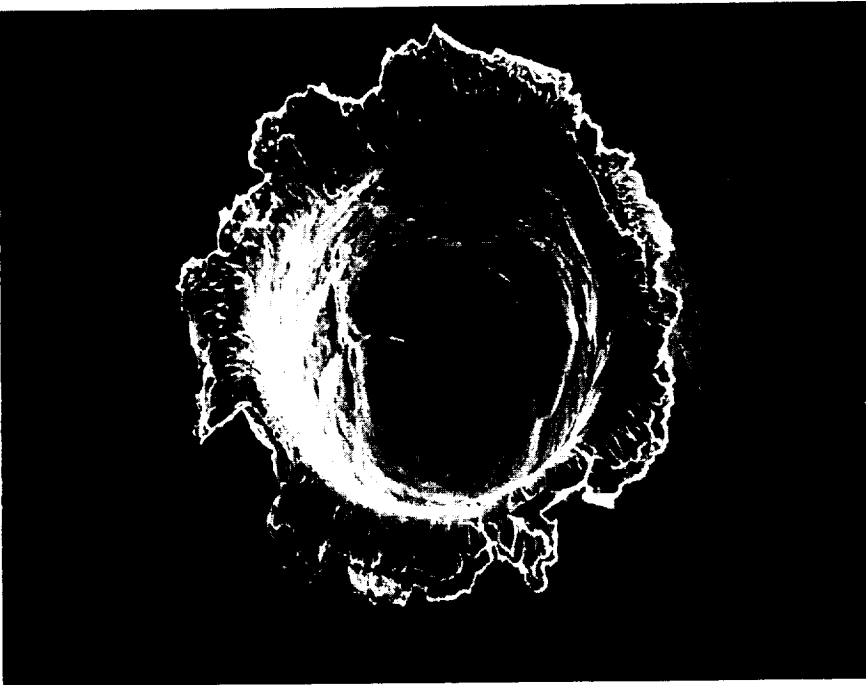


COMPONENT: EOOK
FEATURE: 285
CORE: LD-239
DIAMETER: 195 μm
ORIGIN: Unknown

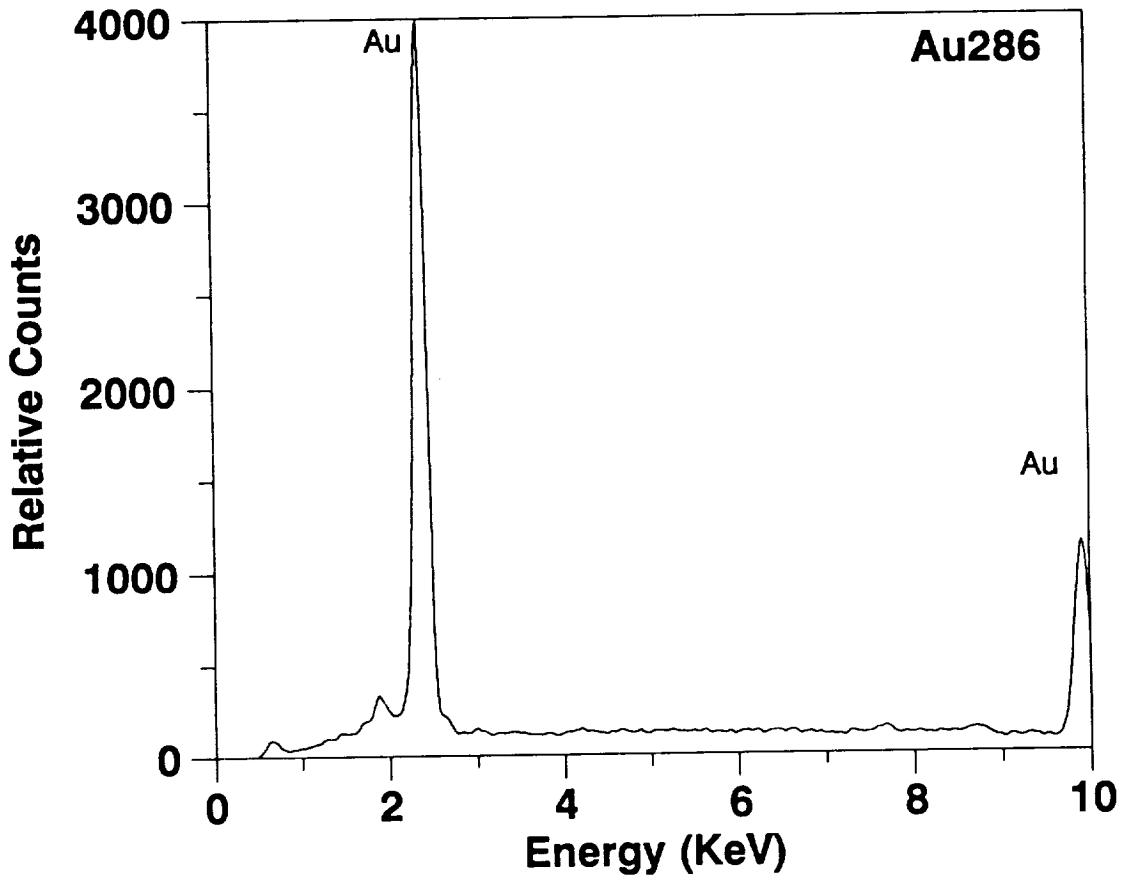


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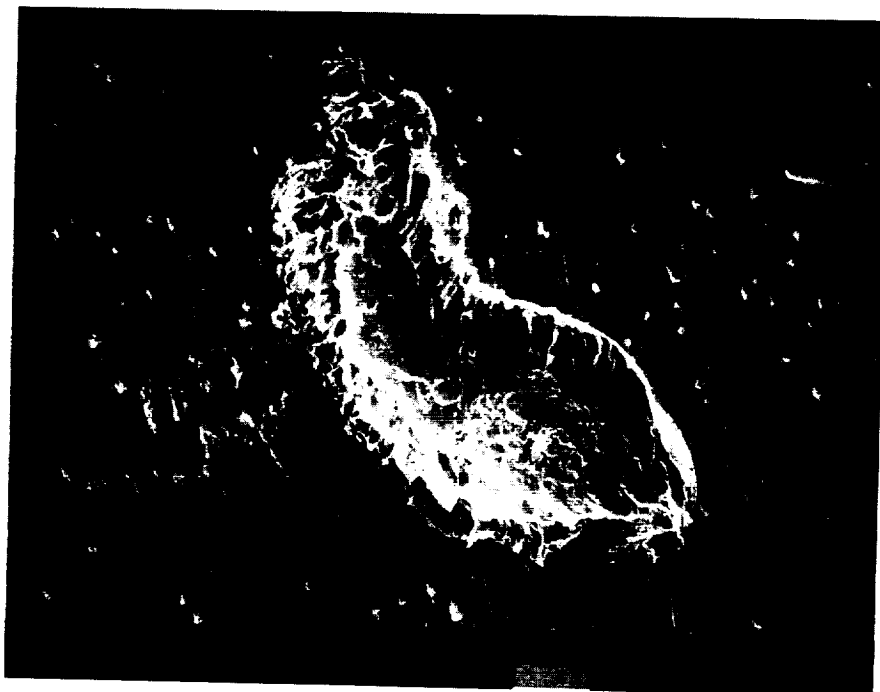


COMPONENT: EOOK
FEATURE: 286
CORE: LD-240
DIAMETER: 85 μ m
ORIGIN: Unknown



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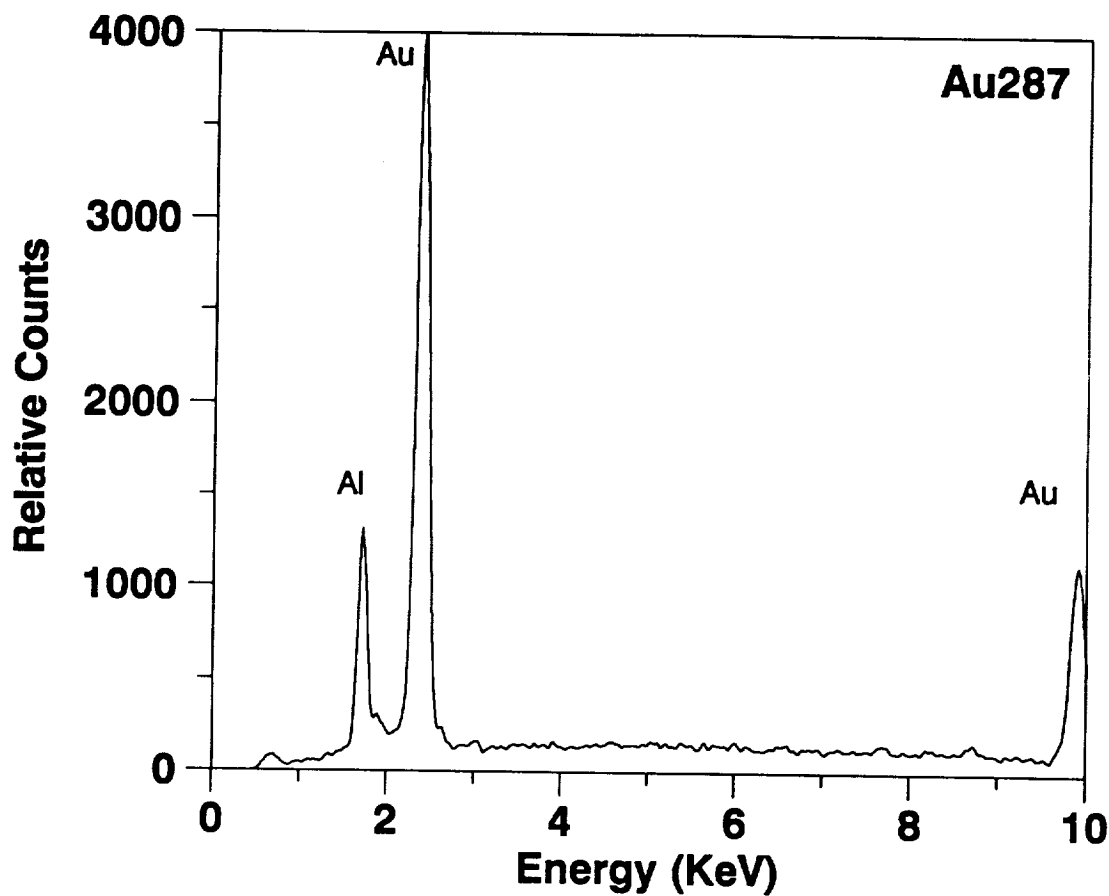
COMPONENT: EOOK

FEATURE: 287

CORE: LD-241

DIAMETER: 145 μm

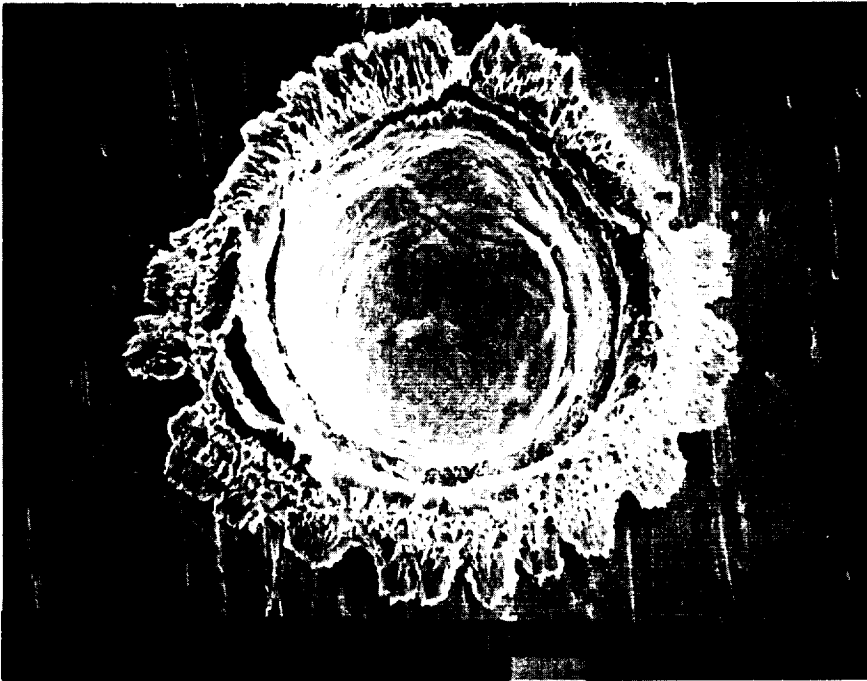
ORIGIN: Man-made



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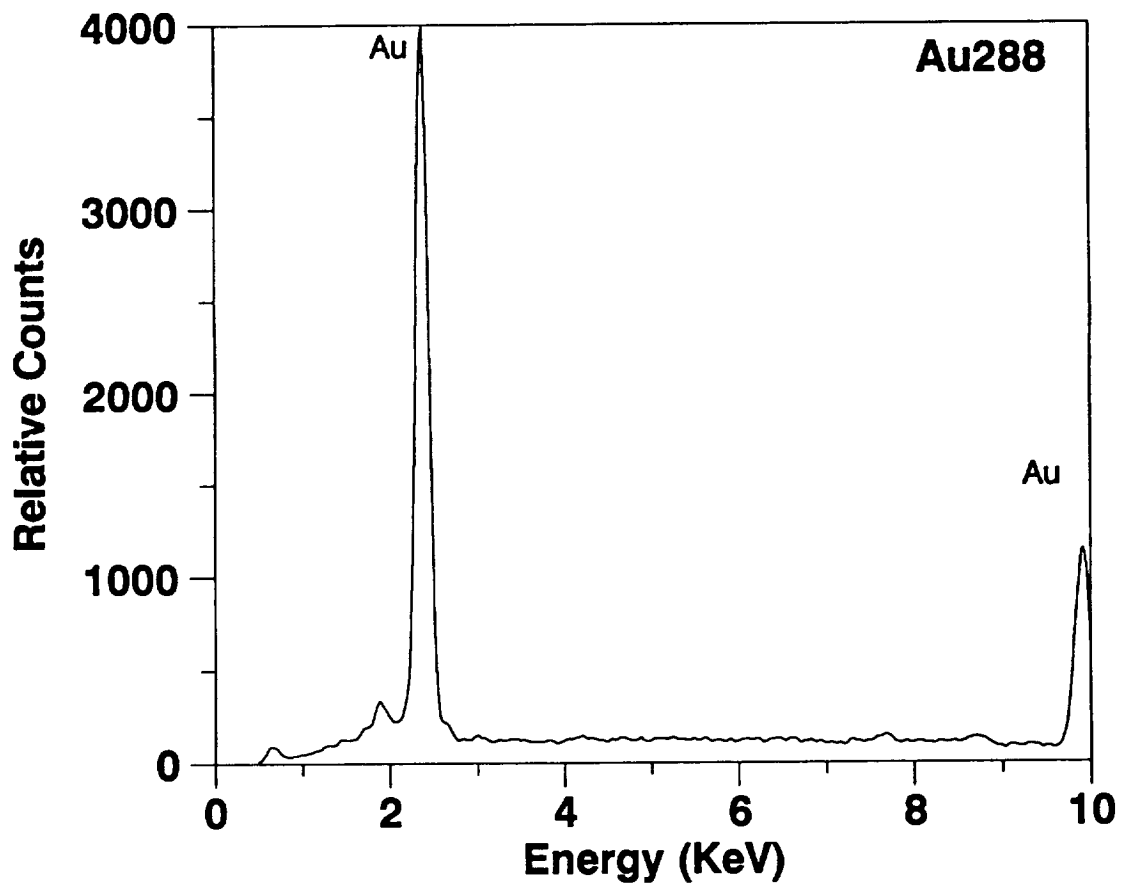
COMPONENT: EOOK

FEATURE: 288

CORE: LD-242

DIAMETER: 55 μm

ORIGIN: Unknown

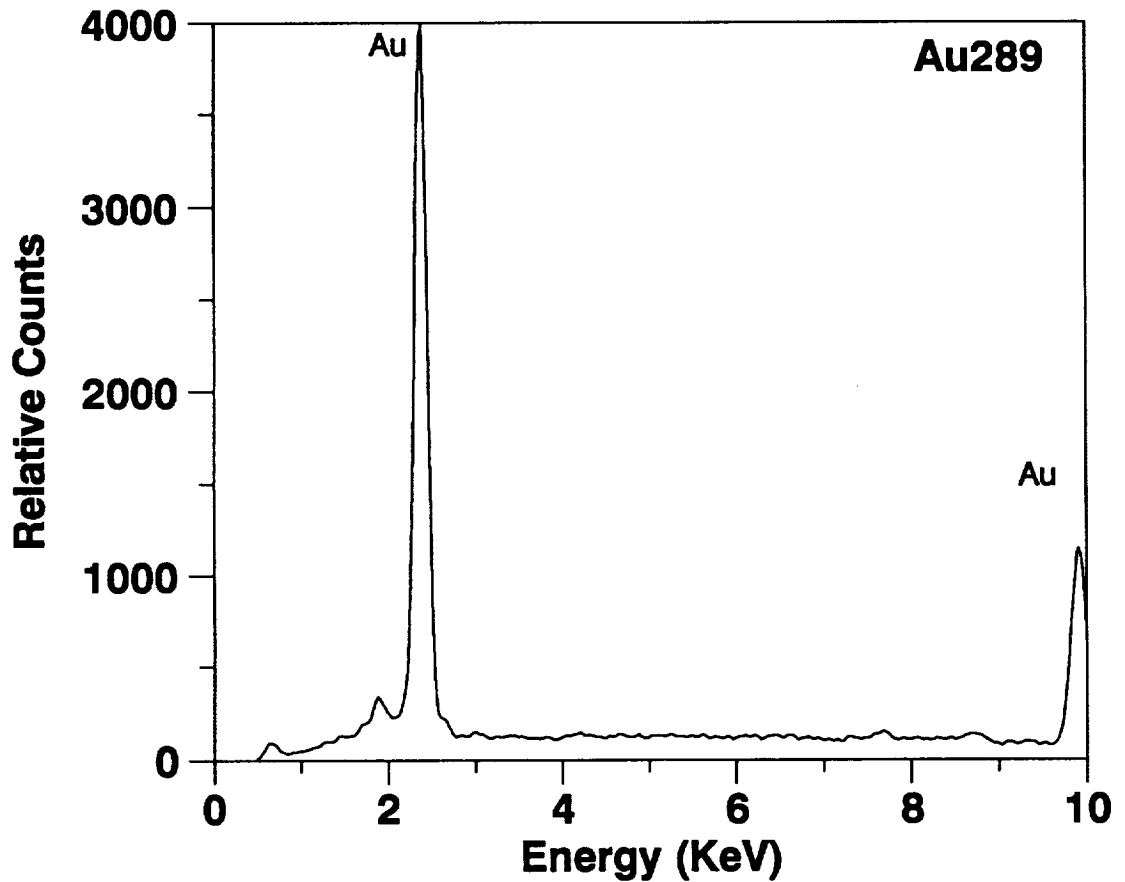


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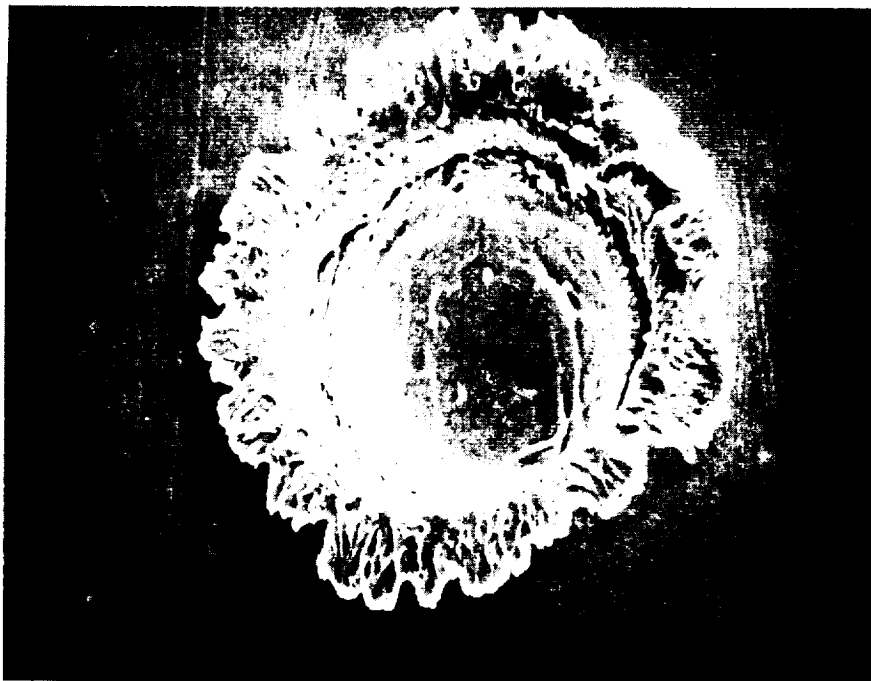


COMPONENT: EOOK
FEATURE: 289
CORE: LD-255
DIAMETER: 260 μ m
ORIGIN: Unknown



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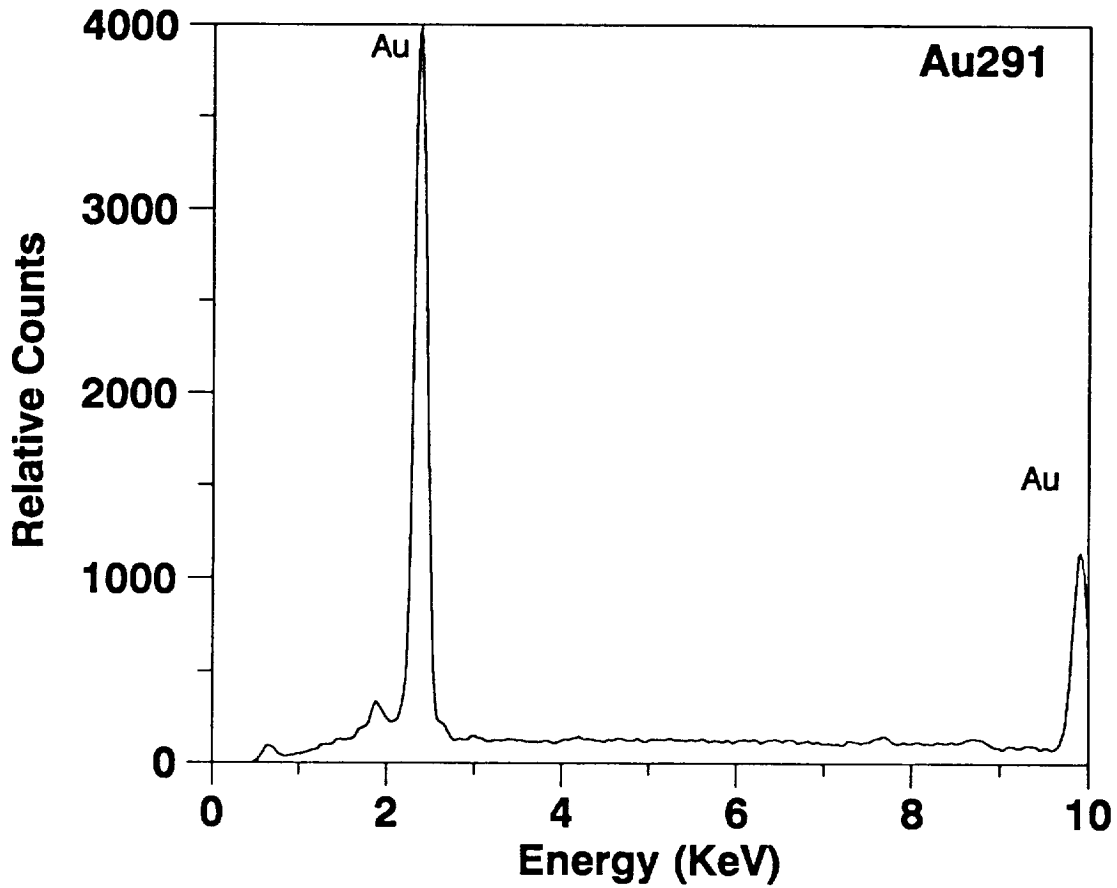
COMPONENT: EOOK

FEATURE: 291

CORE: LD-257

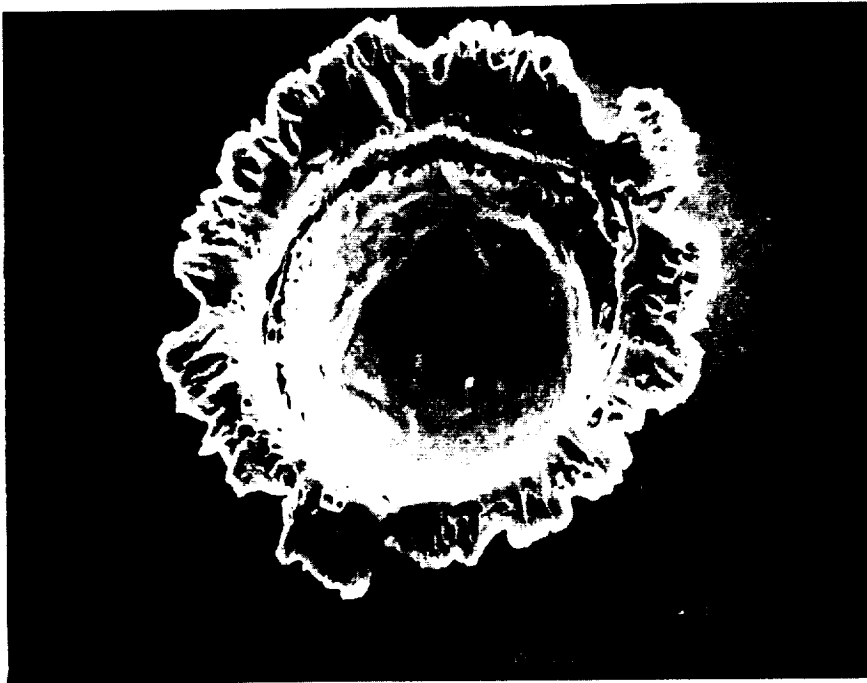
DIAMETER: 35 μ m

ORIGIN: Unknown

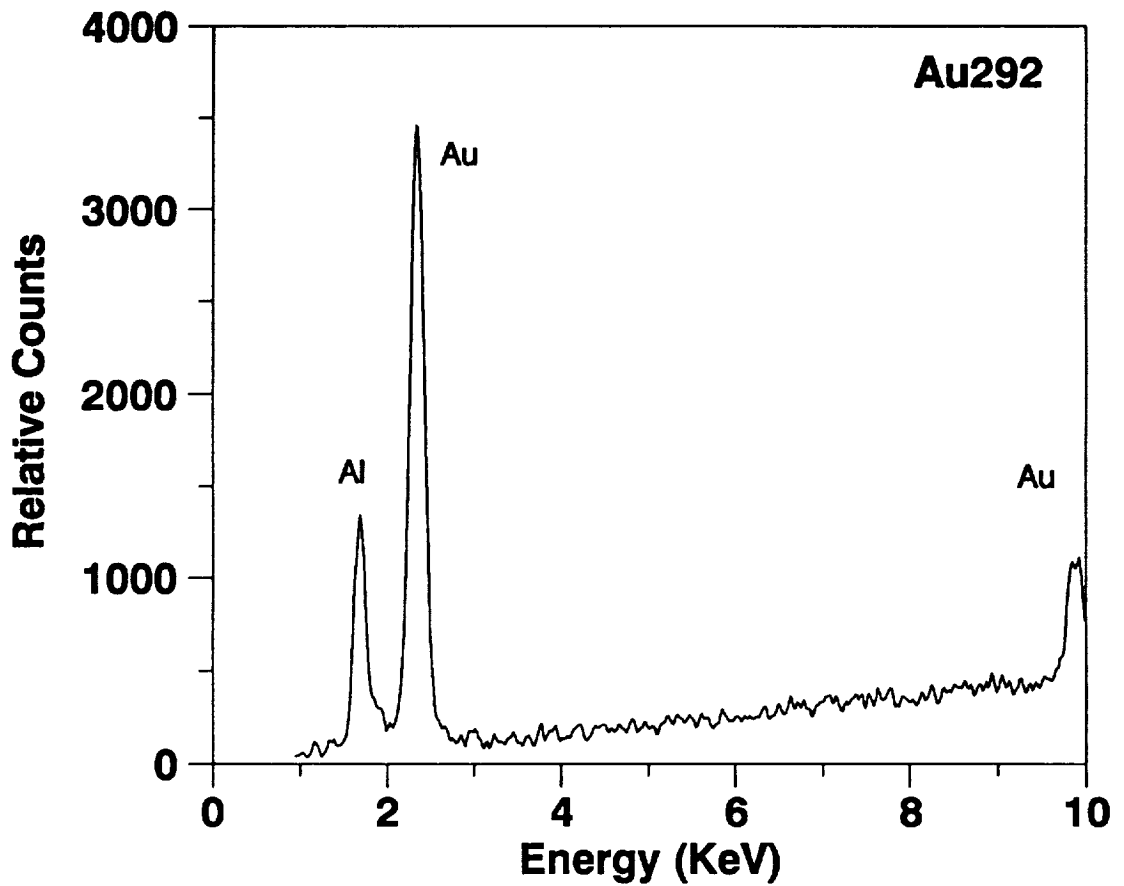


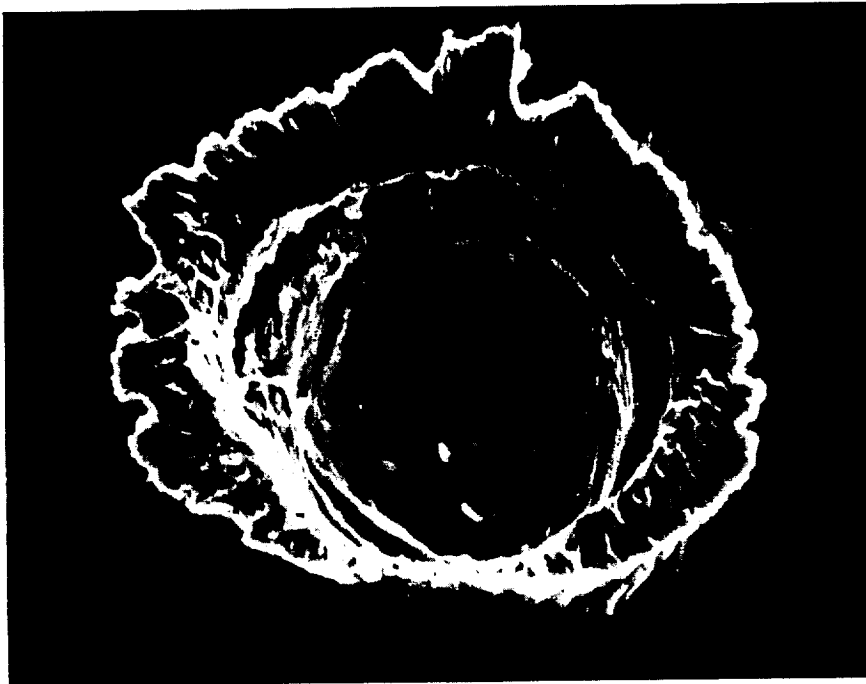
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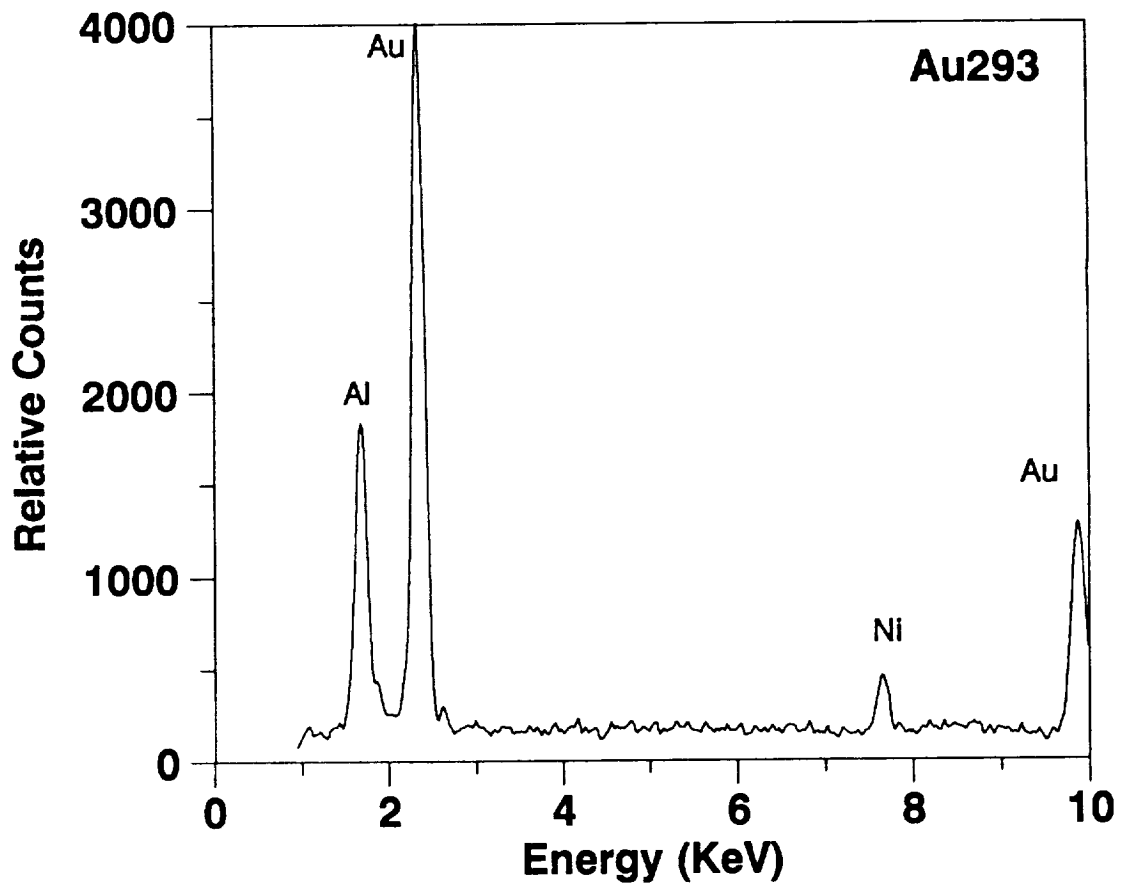


COMPONENT: EOOK
FEATURE: 292
CORE: LD-258
DIAMETER: 15 μm
ORIGIN: Man-made



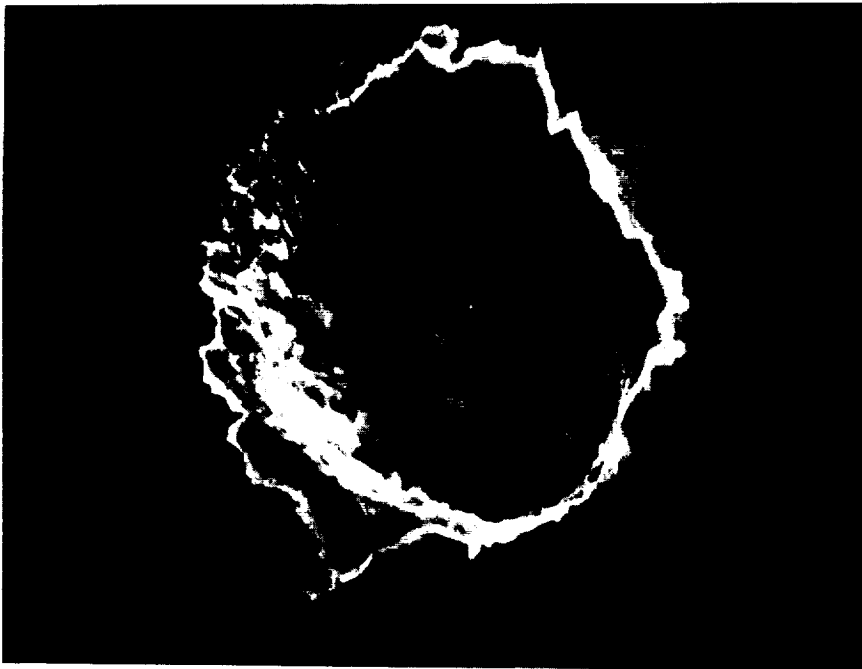


COMPONENT: EOOK
FEATURE: 293
CORE: LD-243
DIAMETER: 15 μm
ORIGIN: Man-made

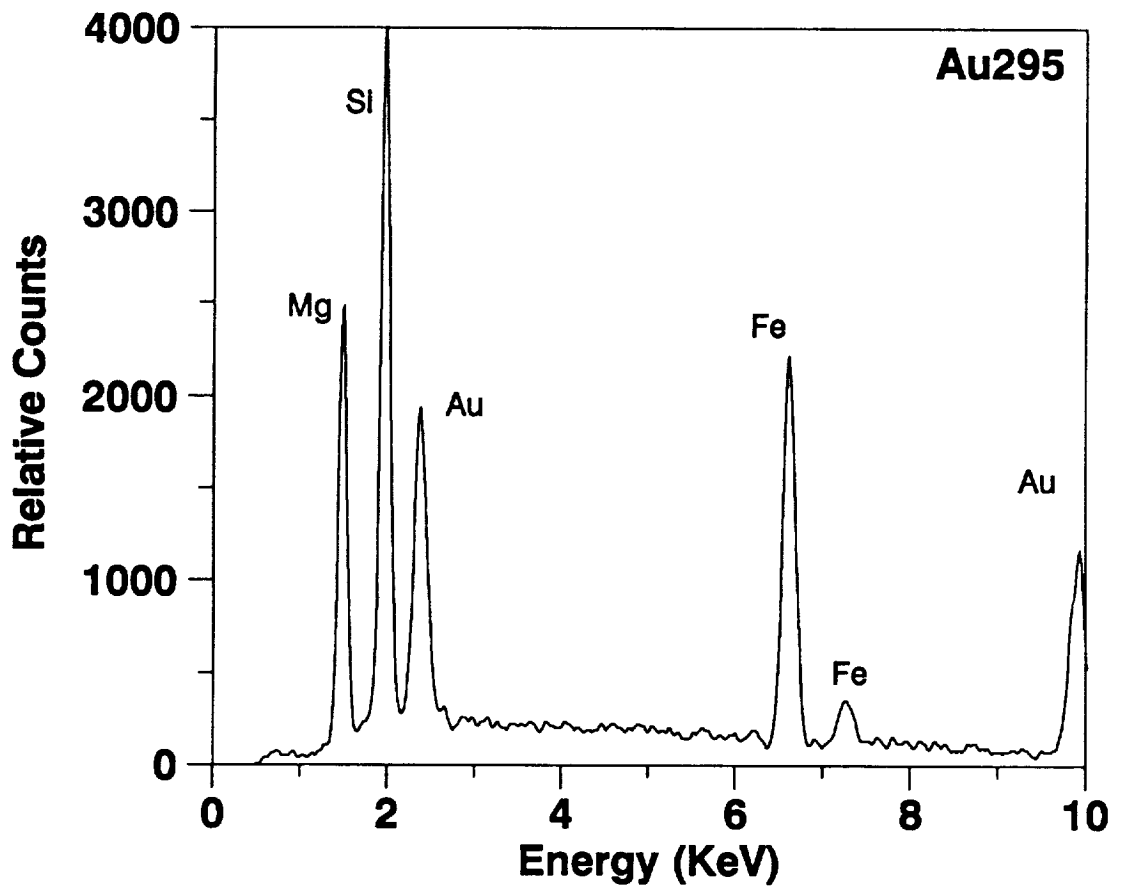


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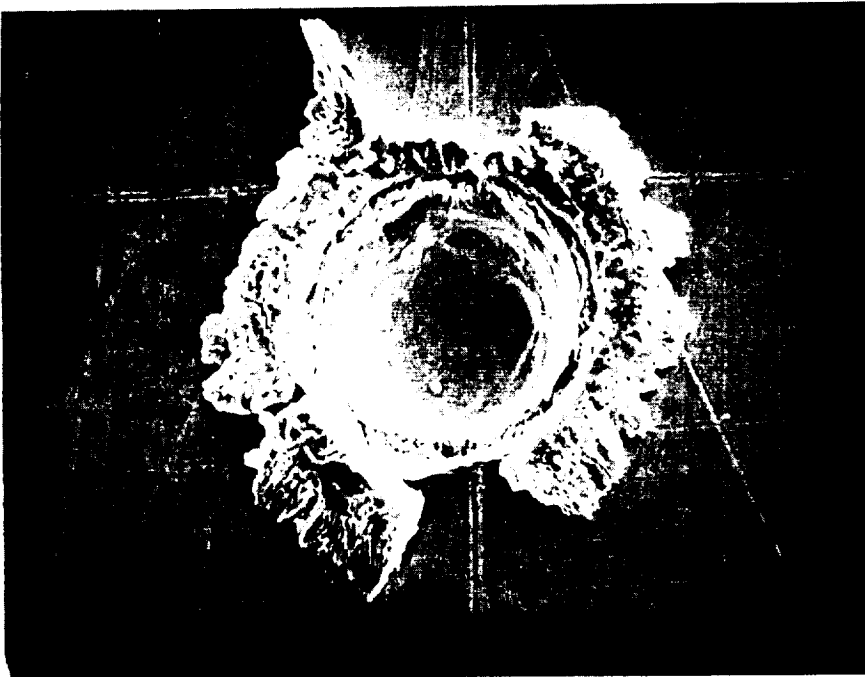


COMPONENT: EOOK
FEATURE: 295
CORE: LD-245
DIAMETER: 15 μ m
ORIGIN: Natural

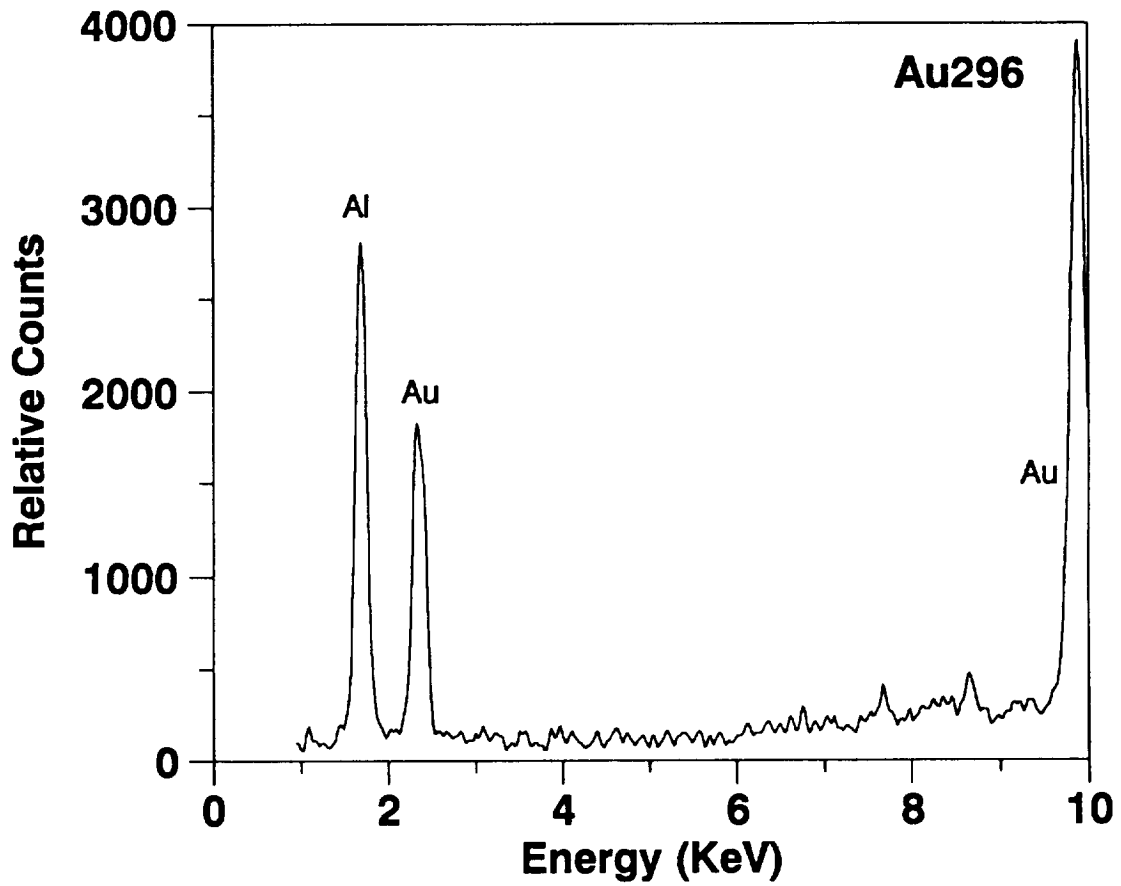


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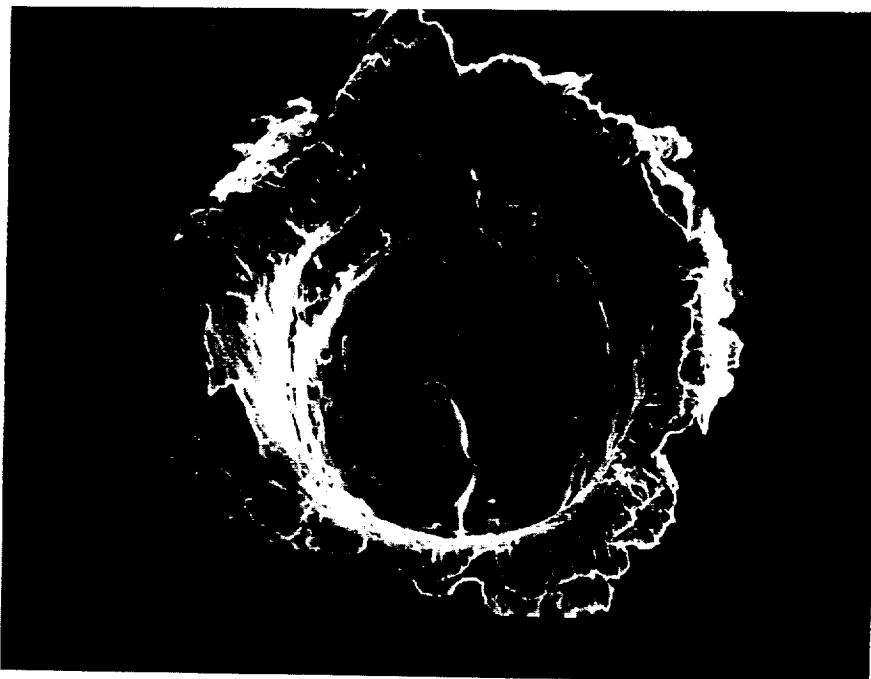


COMPONENT: EOOK
FEATURE: 296
CORE: LD-246
DIAMETER: 20 μm
ORIGIN: Man-made

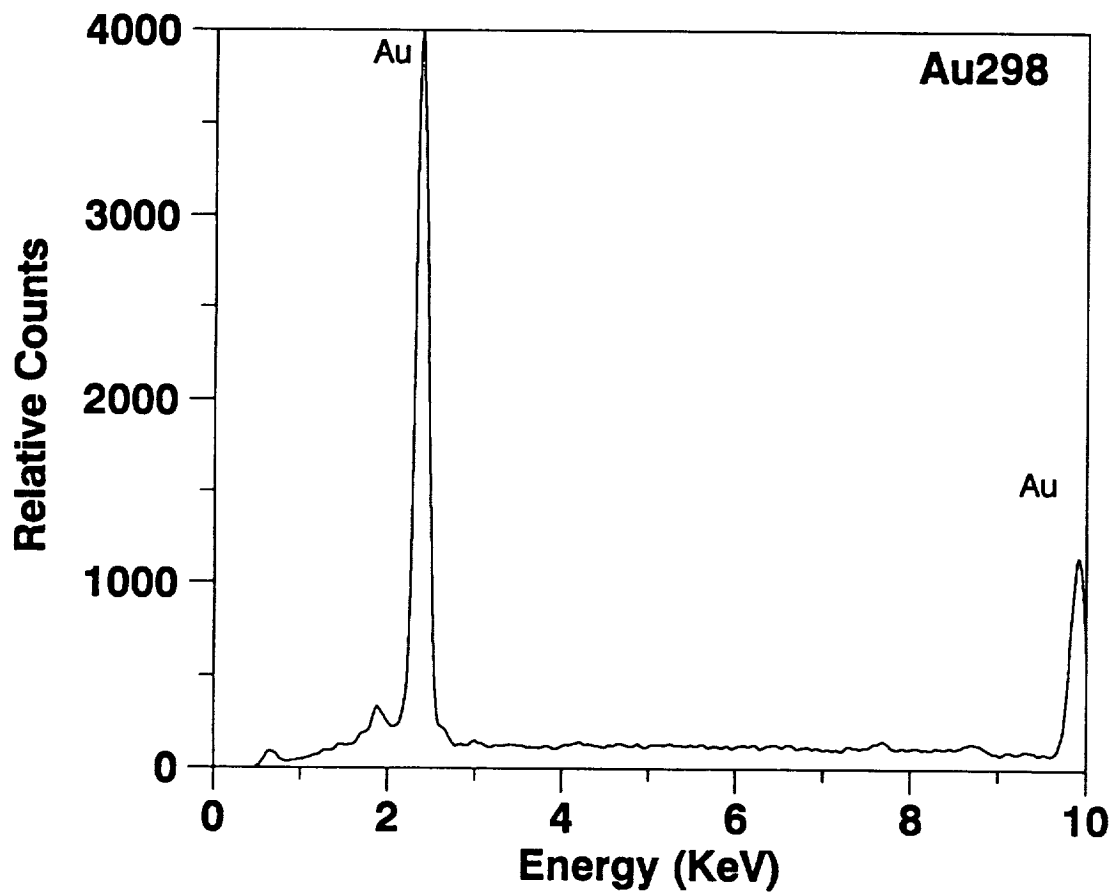


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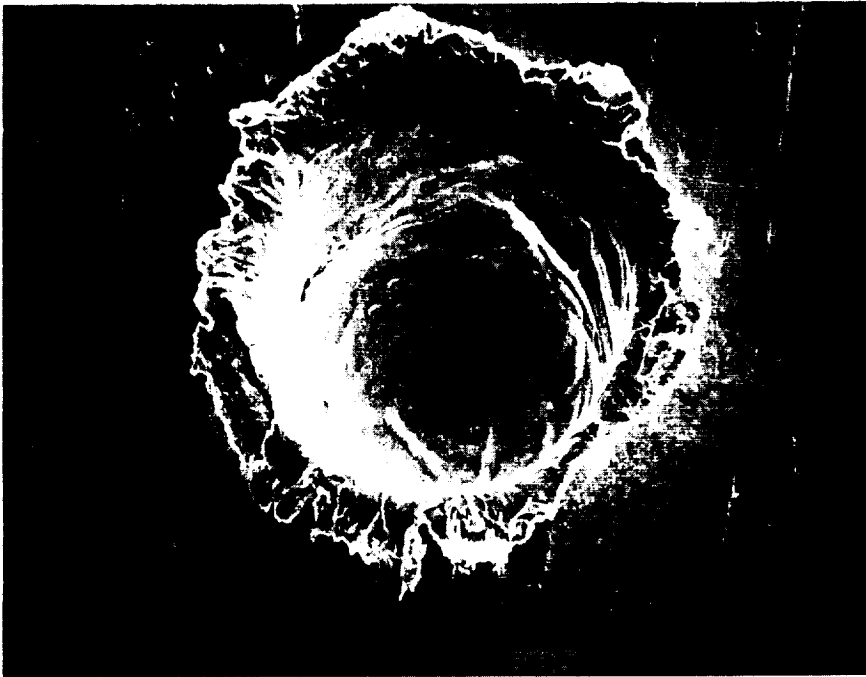


COMPONENT: EOOK
FEATURE: 298
CORE: LD-248
DIAMETER: 85 μ m
ORIGIN: Unknown



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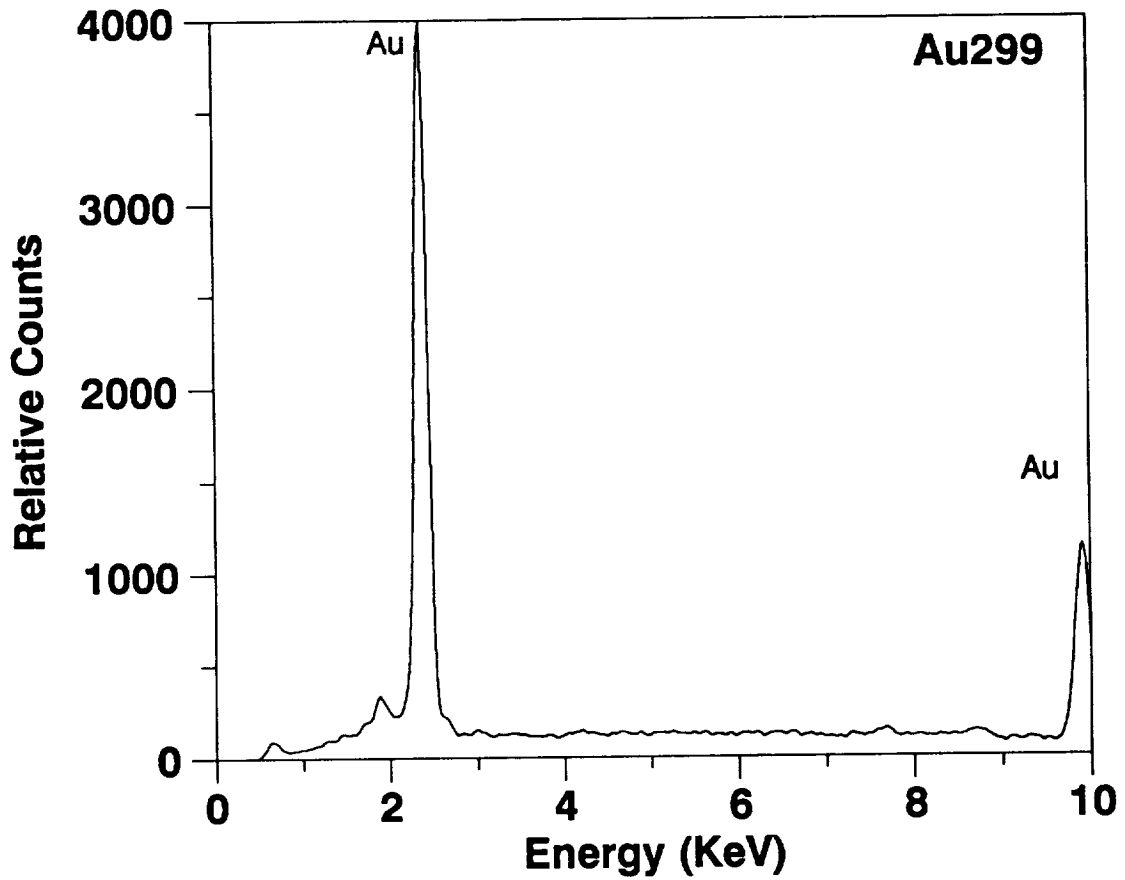
COMPONENT: EOOK

FEATURE: 299

CORE: LD-249

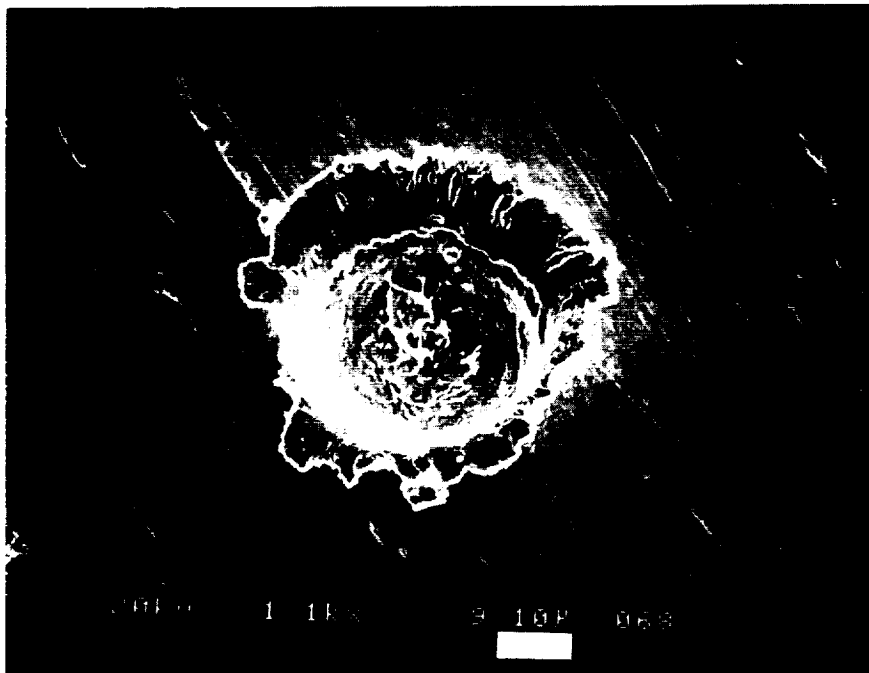
DIAMETER: 80 μm

ORIGIN: Unknown



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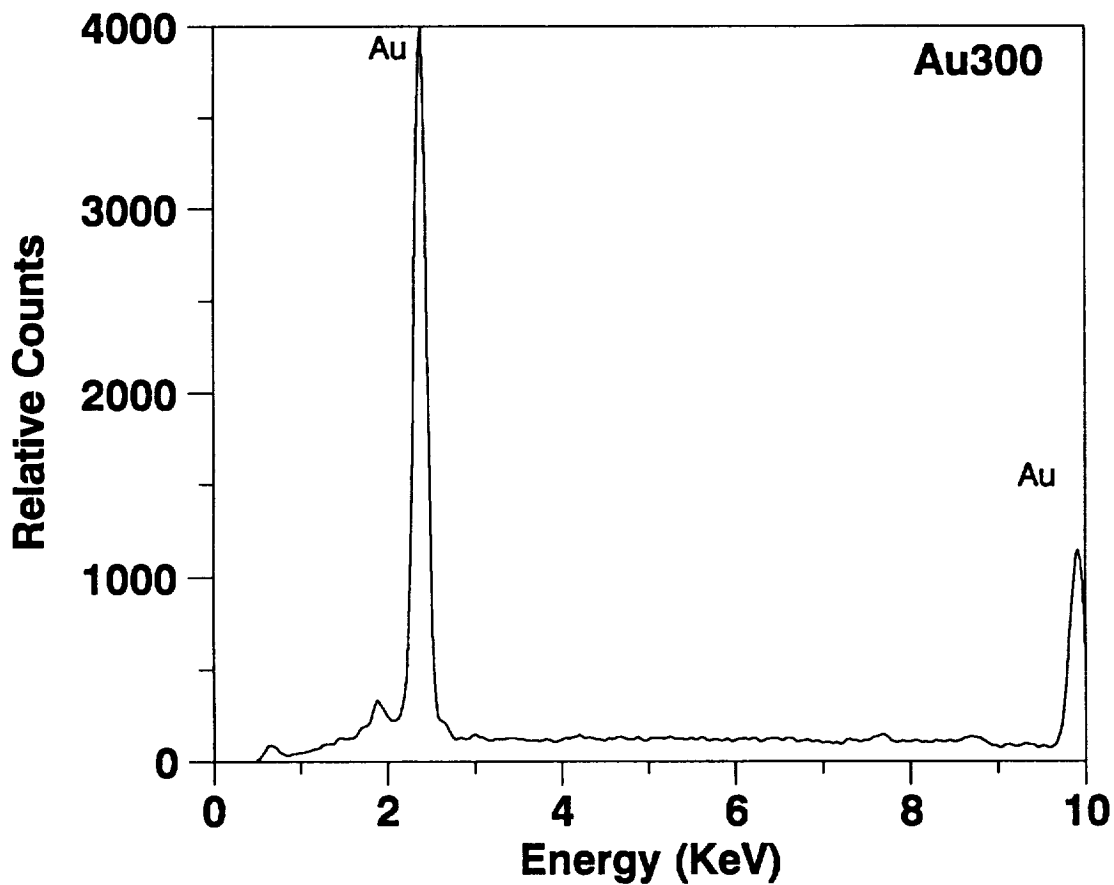
COMPONENT: E00K

FEATURE: 300

CORE: LD-250

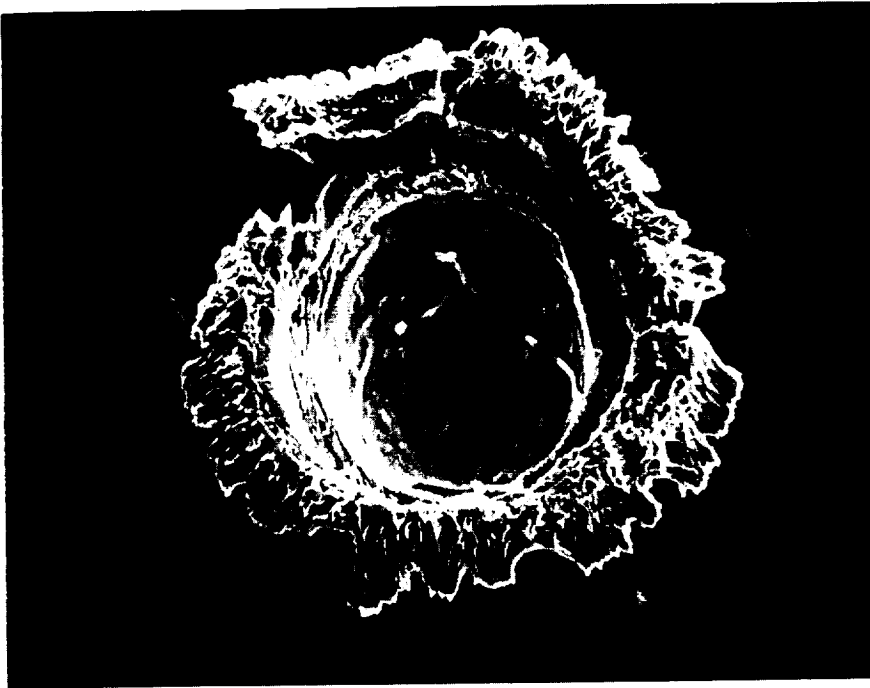
DIAMETER: 35 μm

ORIGIN: Unknown

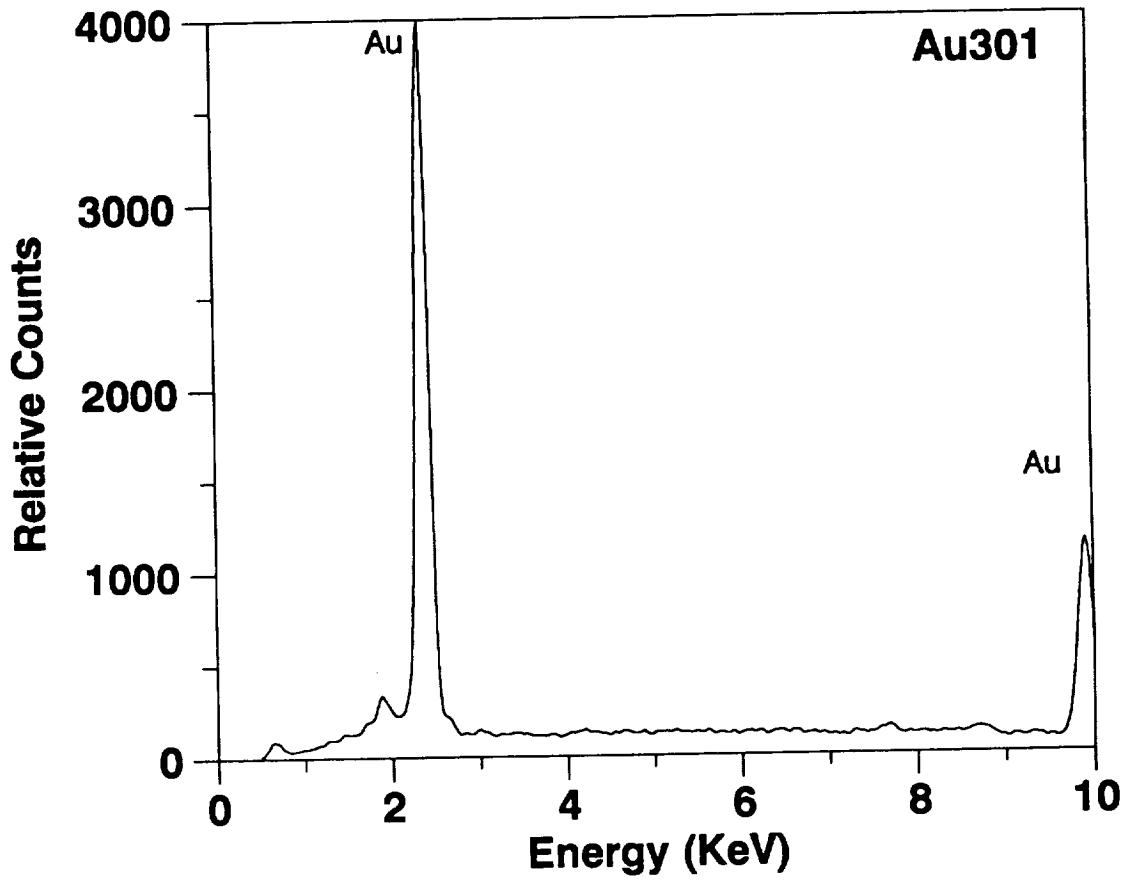


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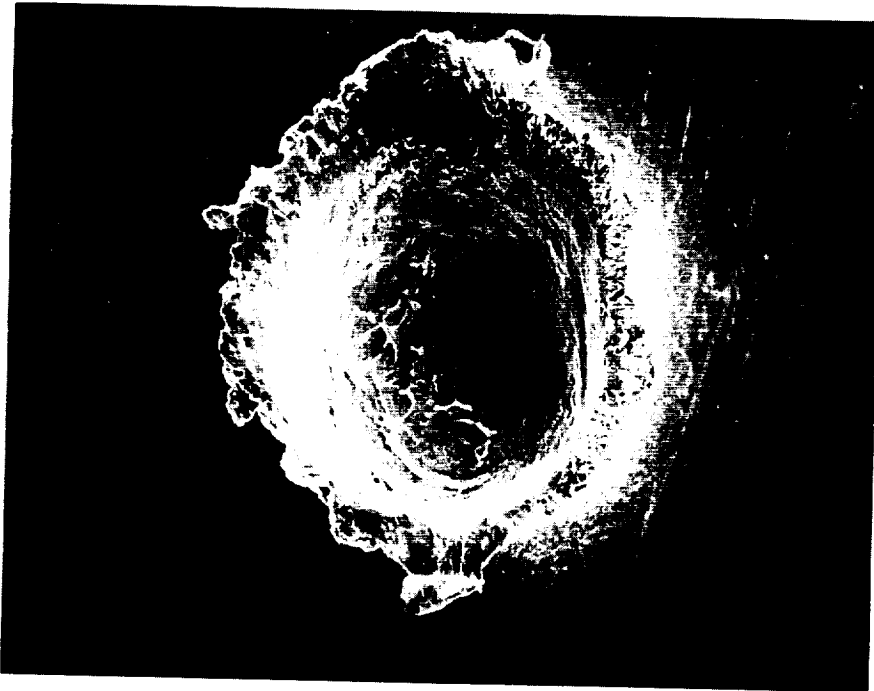


COMPONENT: EOOK
FEATURE: 301
CORE: LD-251
DIAMETER: 45 μ m
ORIGIN: Unknown

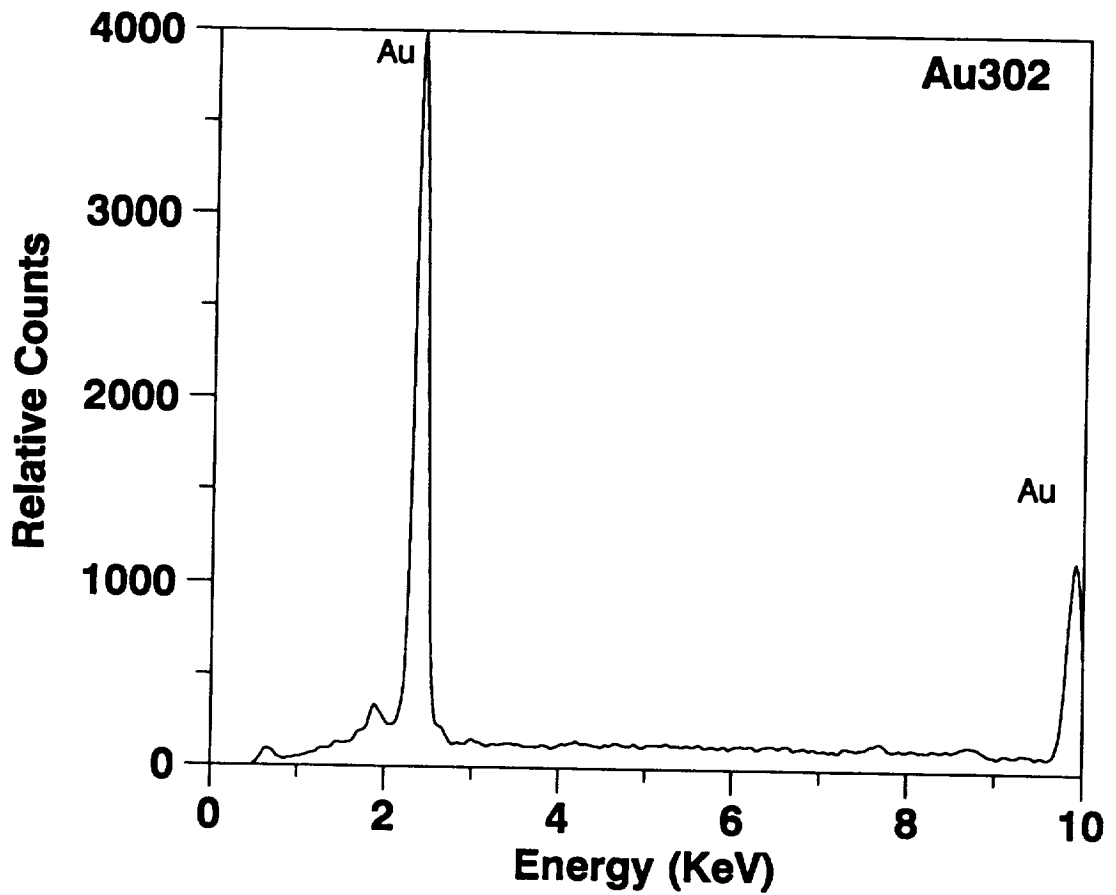


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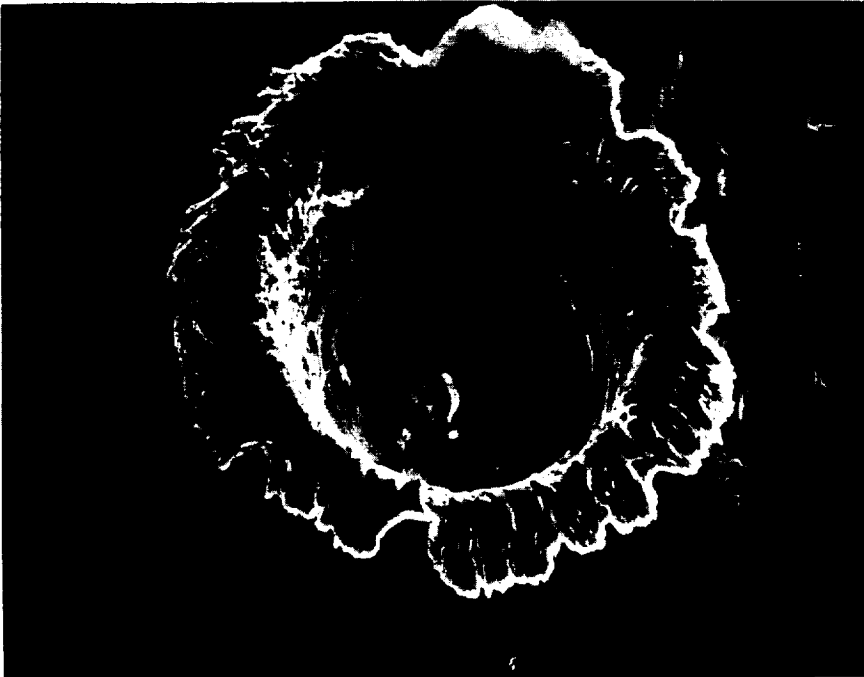


COMPONENT: EOOK
FEATURE: 302
CORE: LD-252
DIAMETER: 125 μm
ORIGIN: Unknown

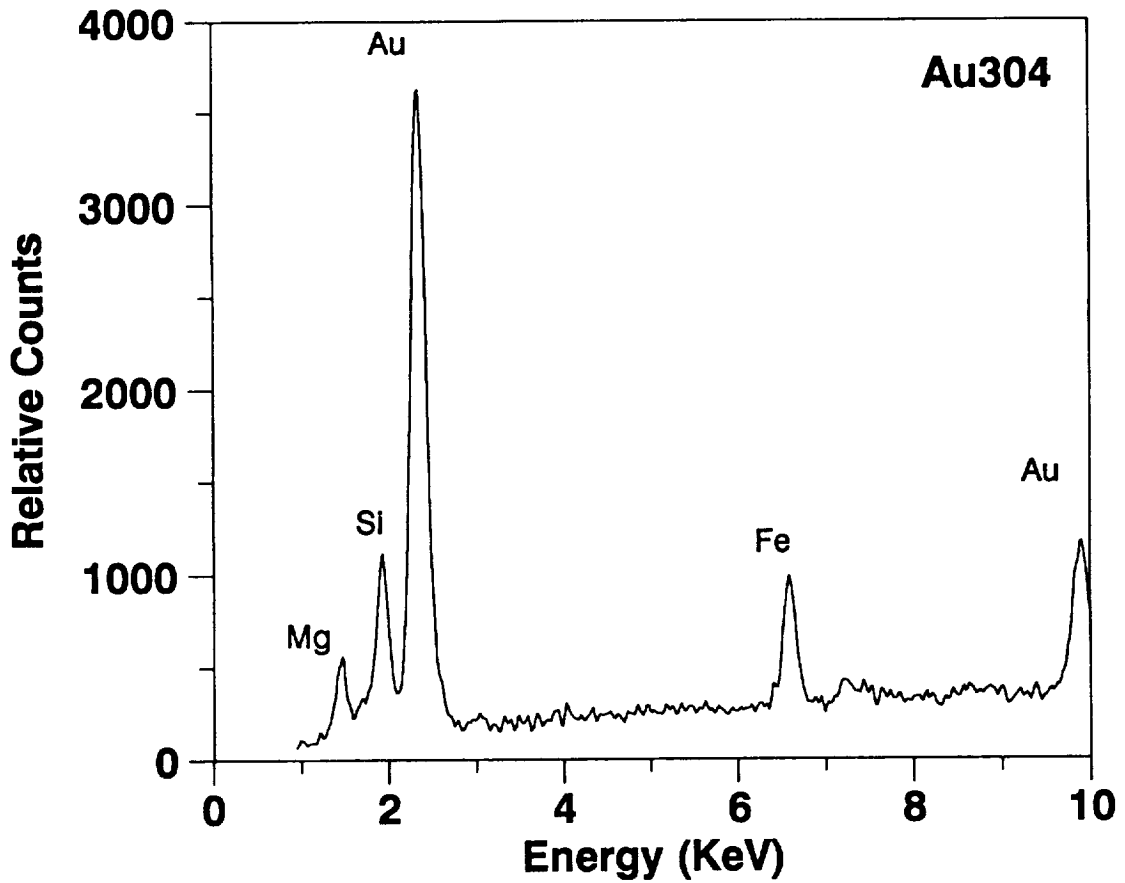


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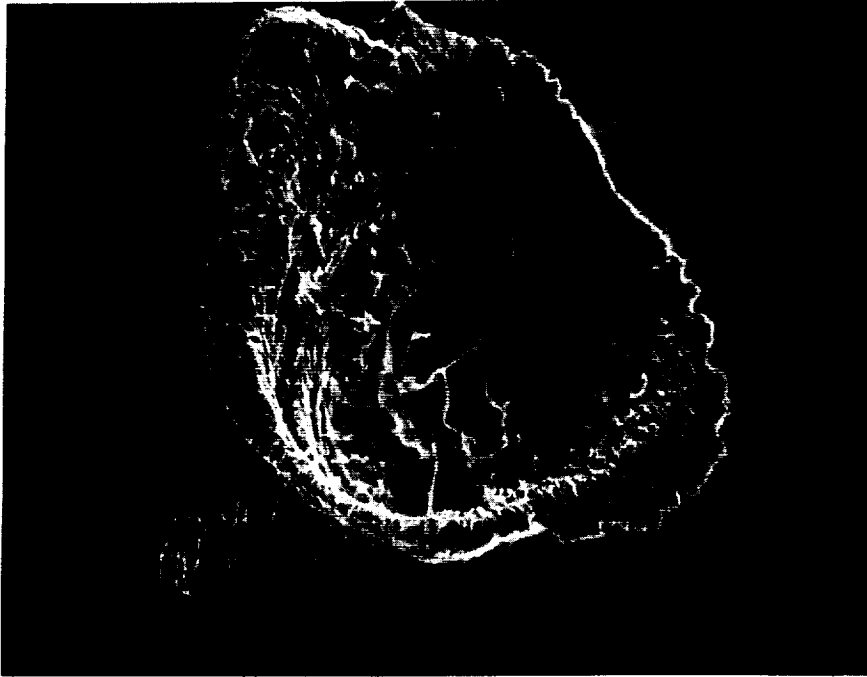


COMPONENT: EOOK
FEATURE: 304
CORE: LD-253
DIAMETER: 20 μm
ORIGIN: Natural



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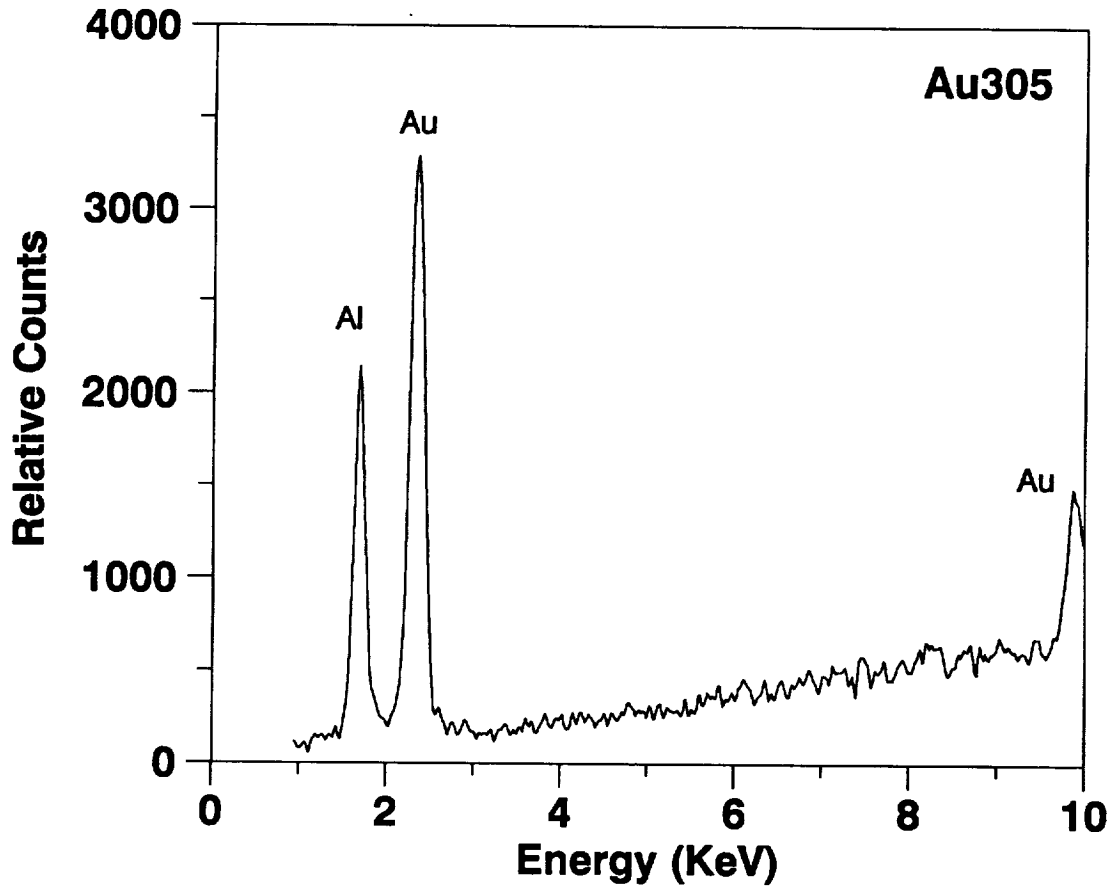
COMPONENT: EOOK

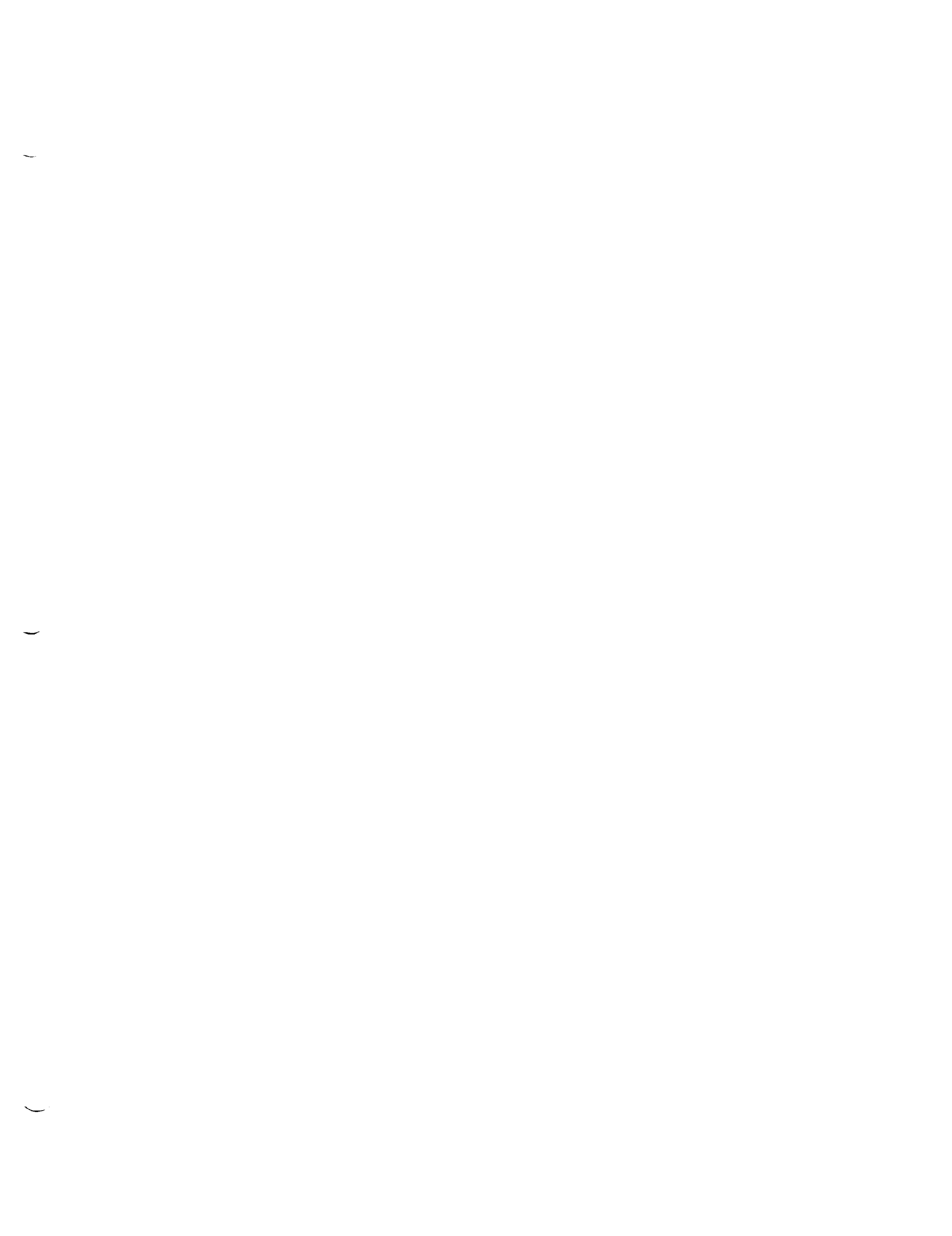
FEATURE: 305

CORE: LD-254

DIAMETER: 45 μm

ORIGIN: Man-made





REPORT DOCUMENTATION PAGE

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13. ABSTRACT (Maximum 200 words) This catalog contains preliminary analyses of residues of hypervelocity projectiles that encountered gold substrates exposed by instrument A0187-1 on the Long Duration Exposure Facility (LDEF). This instrument was on LDEF's trailing edge where relative encounter speeds should be lowest for any non-spinning platform in low Earth orbit (LEO). Approximately 0.6m ² of Au substrates yielded 198 impact craters >20 micrometers in diameter. Some 30% of the craters were made by natural cosmic dust particles and some 15% by man-made objects. Some 50% of all features, however, have residues, if any, that are beyond the detection threshold of the SEM-EDXA method used. The purpose of this catalog is to provide detailed evidence and criteria that may be used to arrive at specific particle types on a case-by-case basis and to group such particles into compositional classes. Clearly this is a somewhat interpretative undertaking. For that reason, we encourage and solicit critique and comments from those interested in the systematic analysis of all impact features on LDEF>				
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