NASA Technical Memorandum 104750

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 0.8m 2 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 (EOOE-EOOK) 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

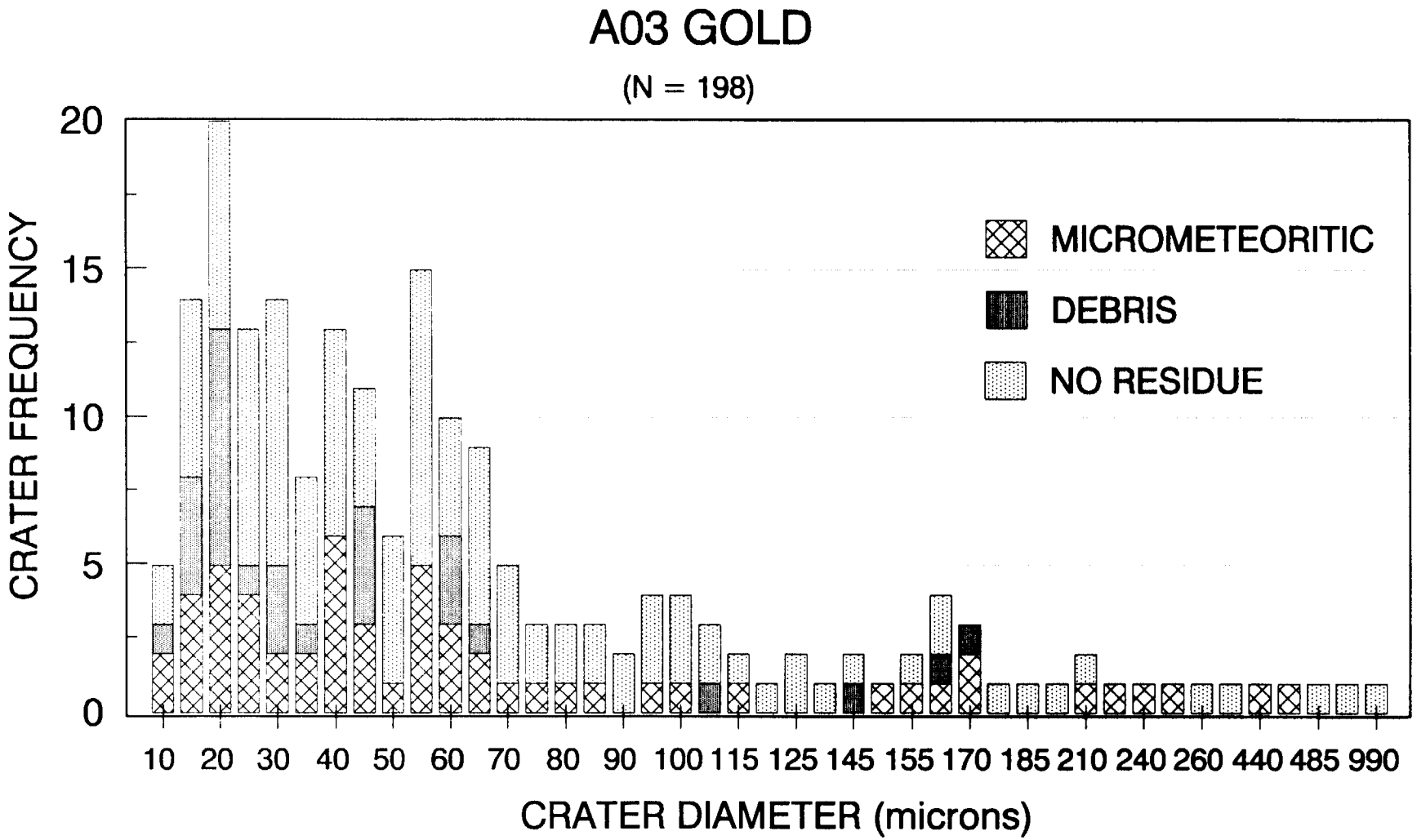
These contain Si, Mg, Ca and Fe in variable proportions typical for mafic silicates, such as olivine or pyroxene. While also mostly molten, some of these craters contain fragments of the above minerals, typically in clusters, i.e. fragments of a larger parent-crystal. Some of the melts have chondritic 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)
CRATER FREQUENCY
20
15
10
5
0
MICROMETEORITIC
DEBRIS
NO RESIDUE
10 20 30 40 50 60 70 80 90 100 115 125 145 155 170 185 210 240 260 440 485 990
CRATER DIAMETER (microns)

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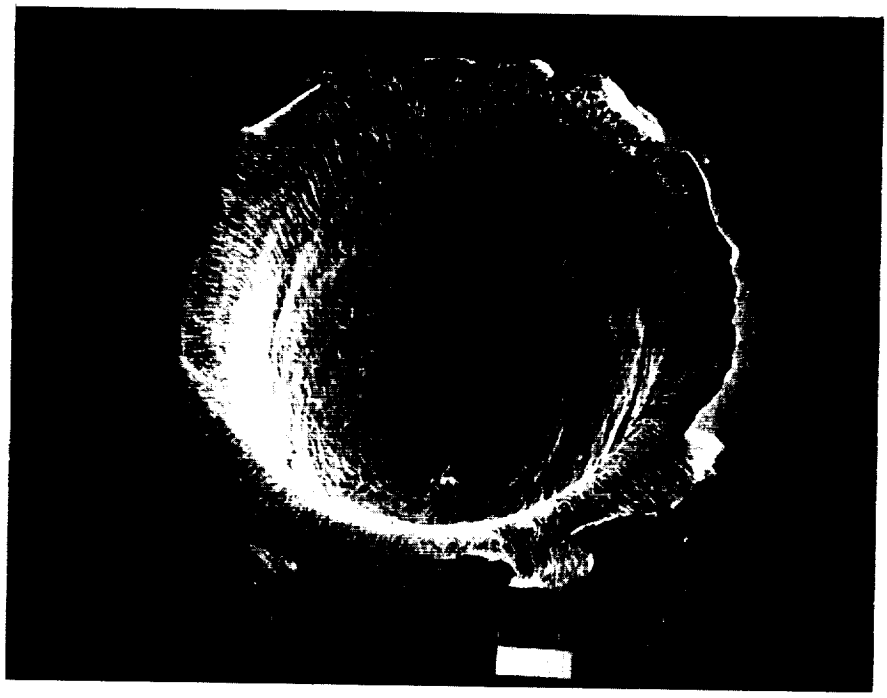

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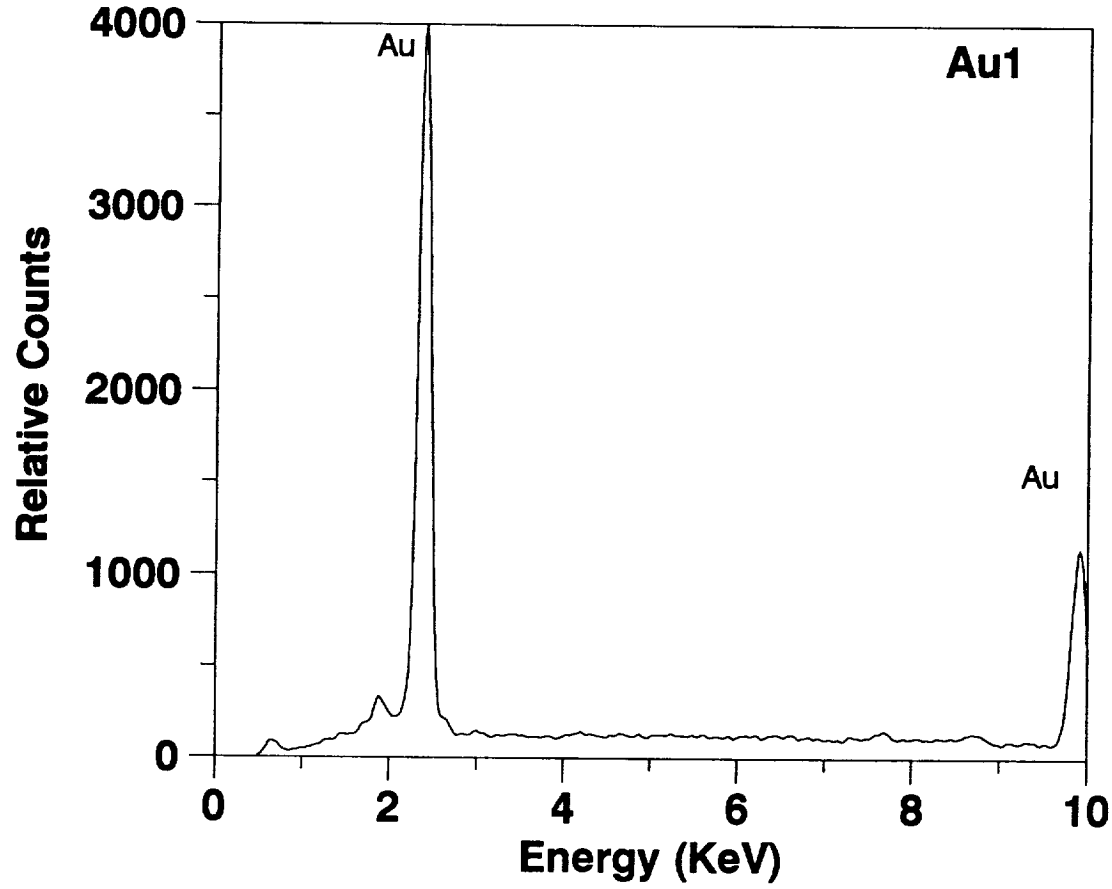

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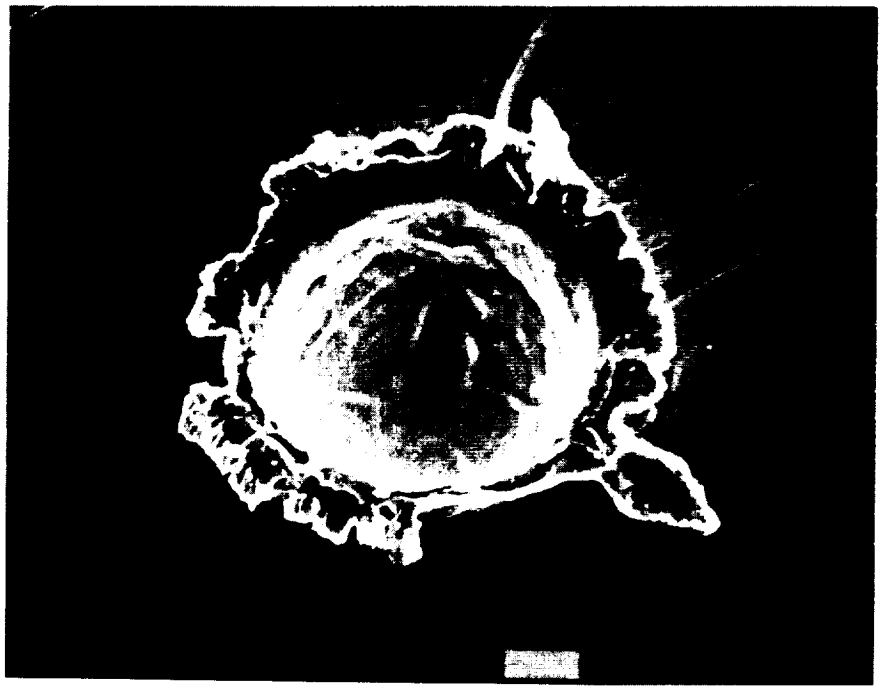

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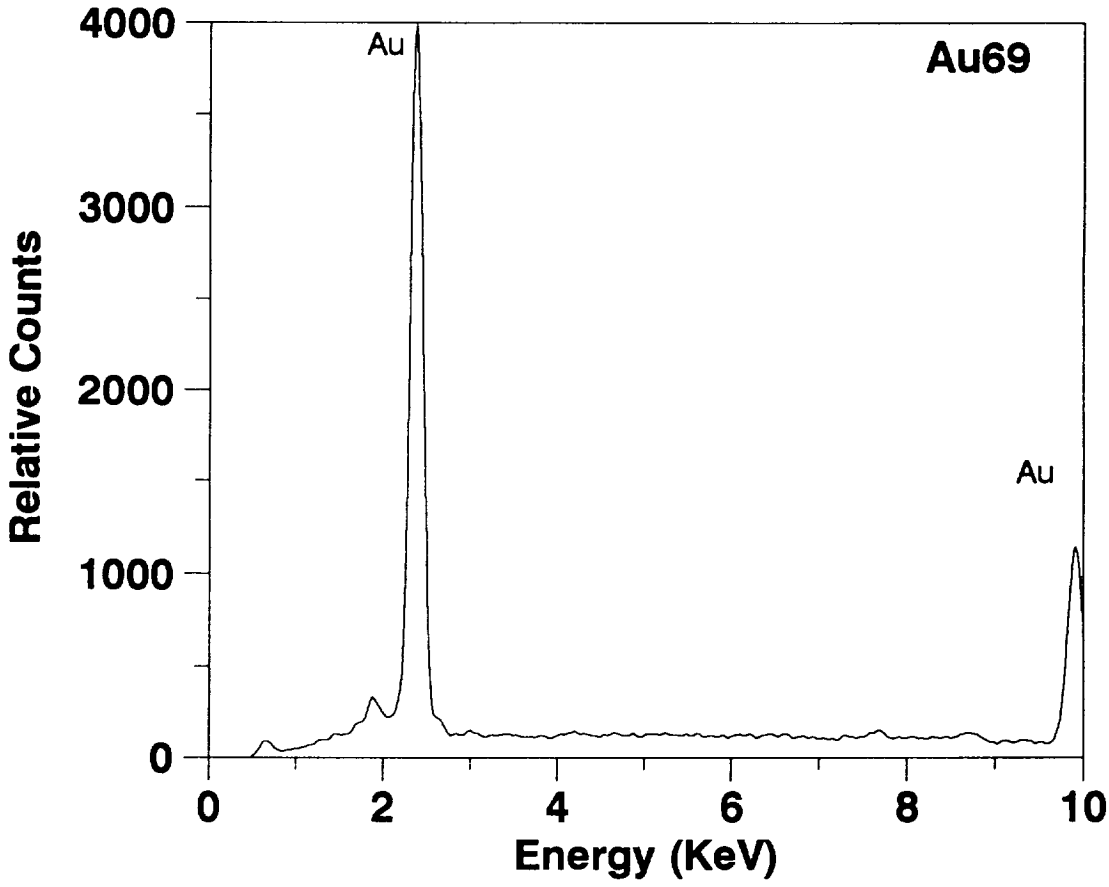

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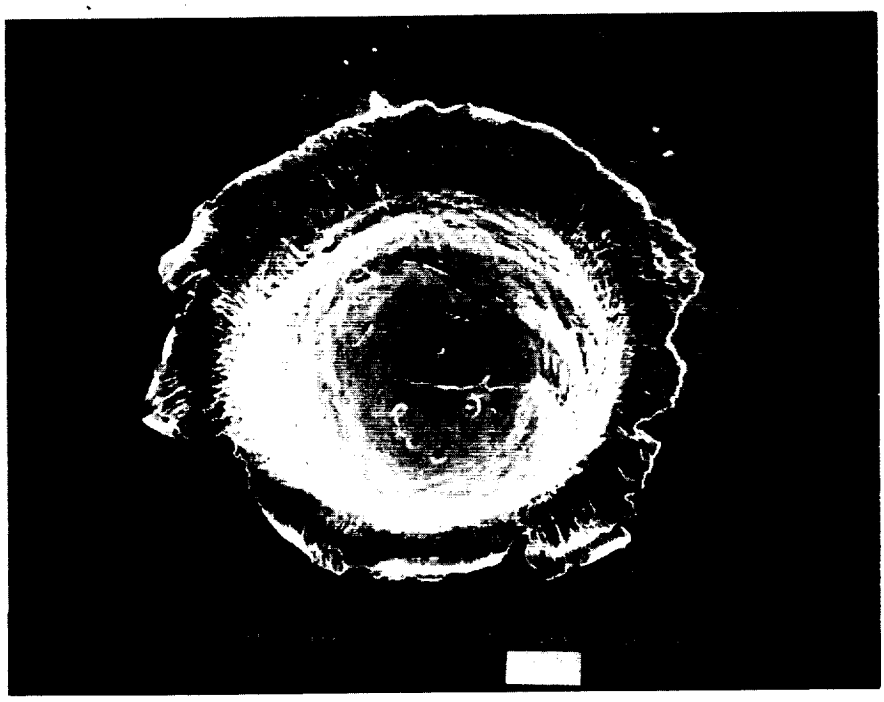

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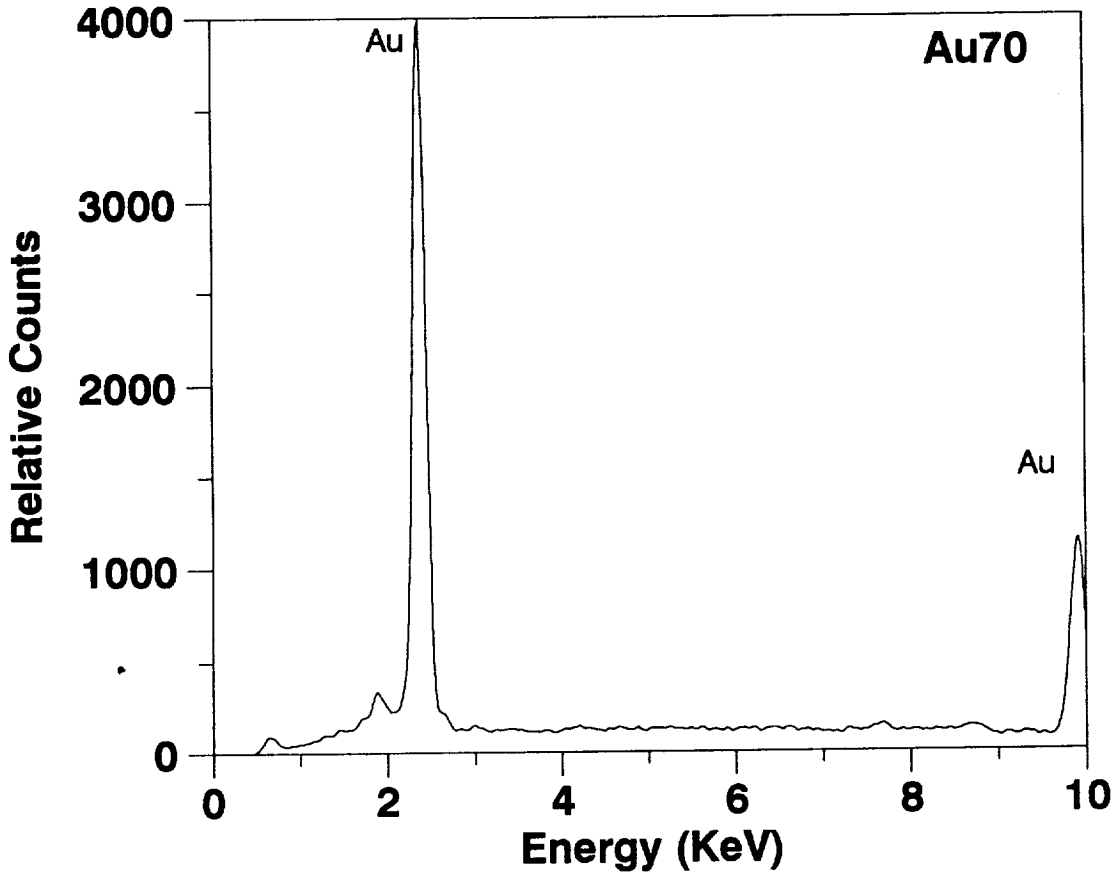

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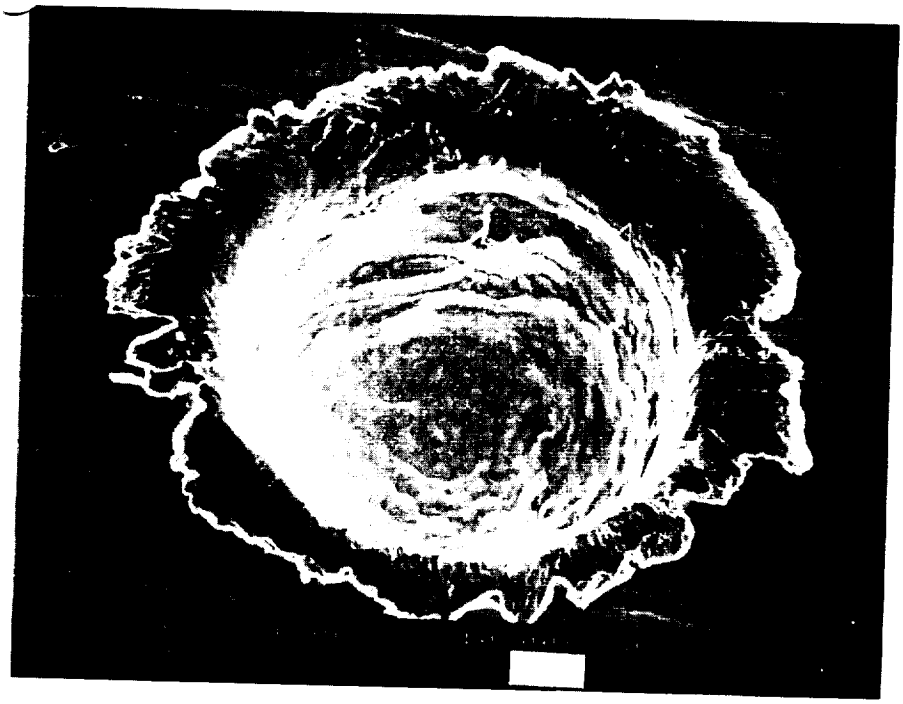

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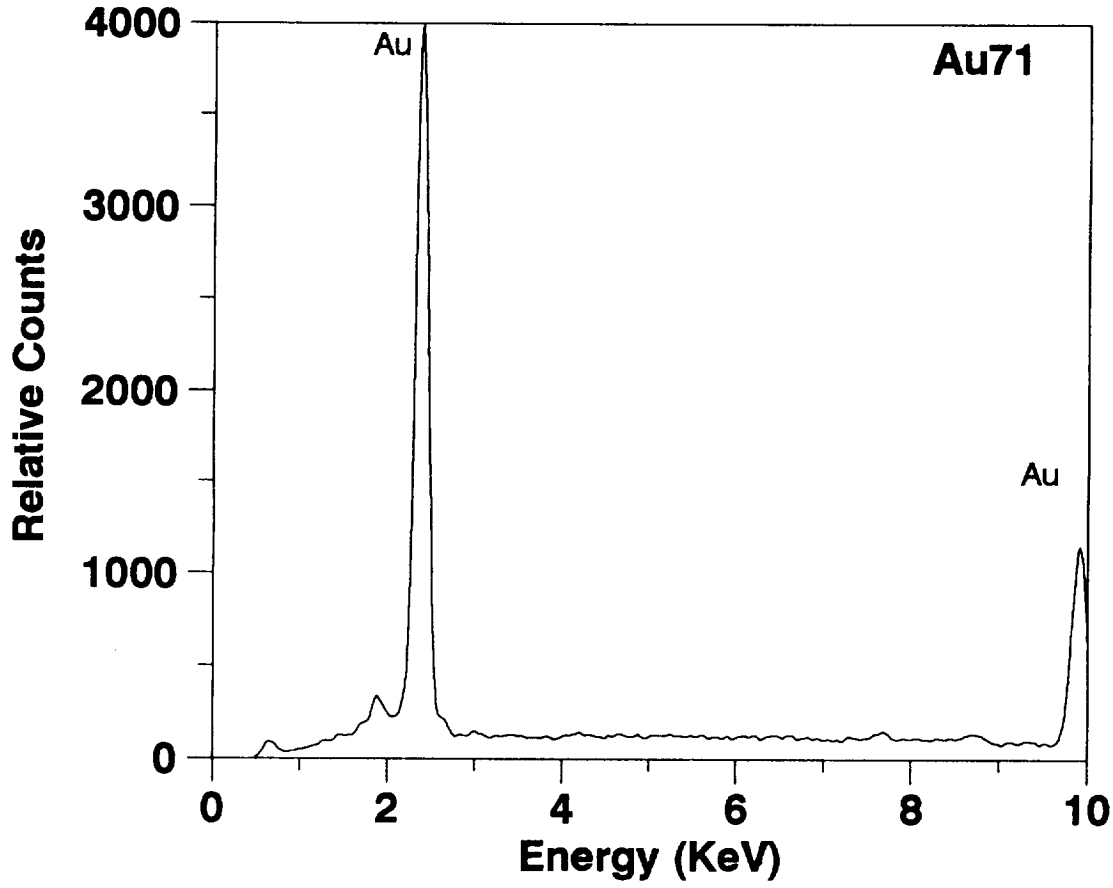

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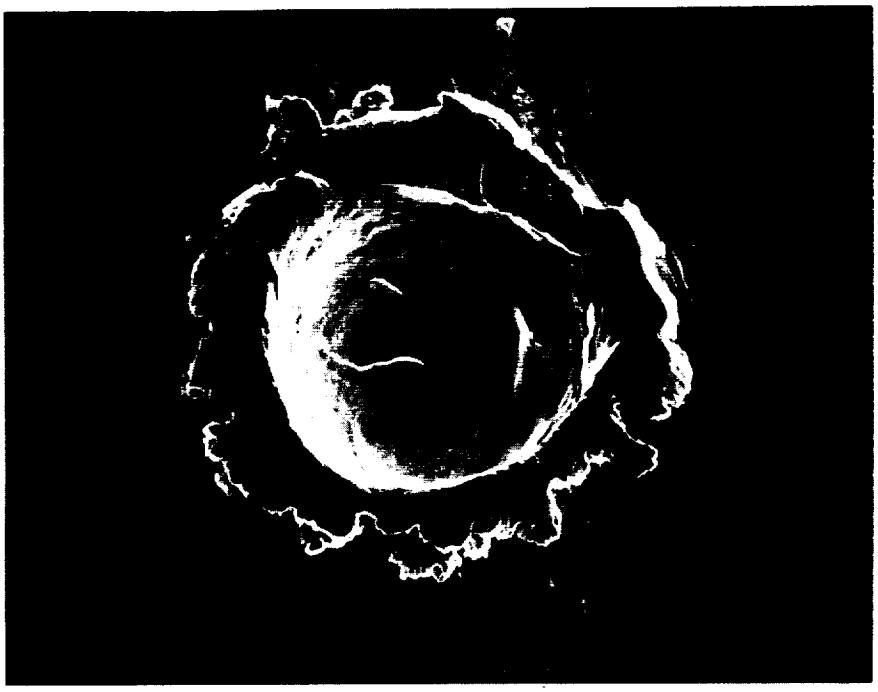

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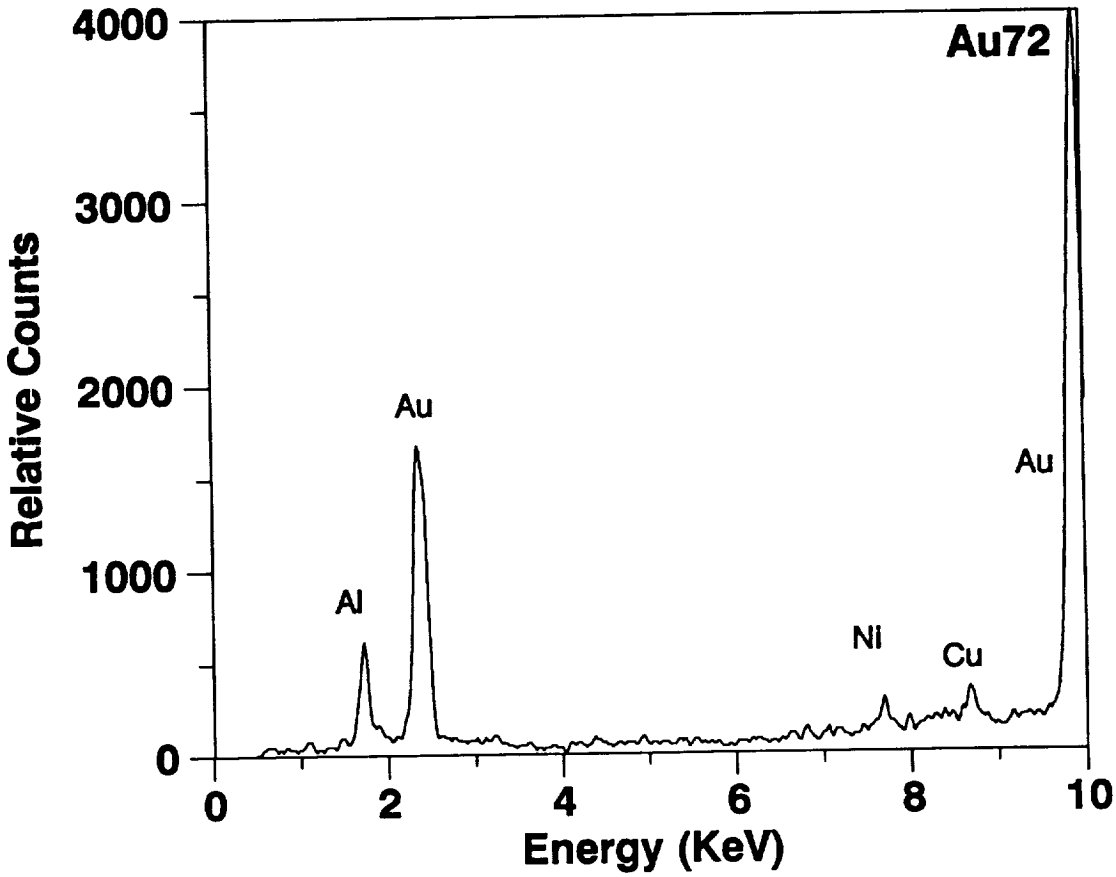

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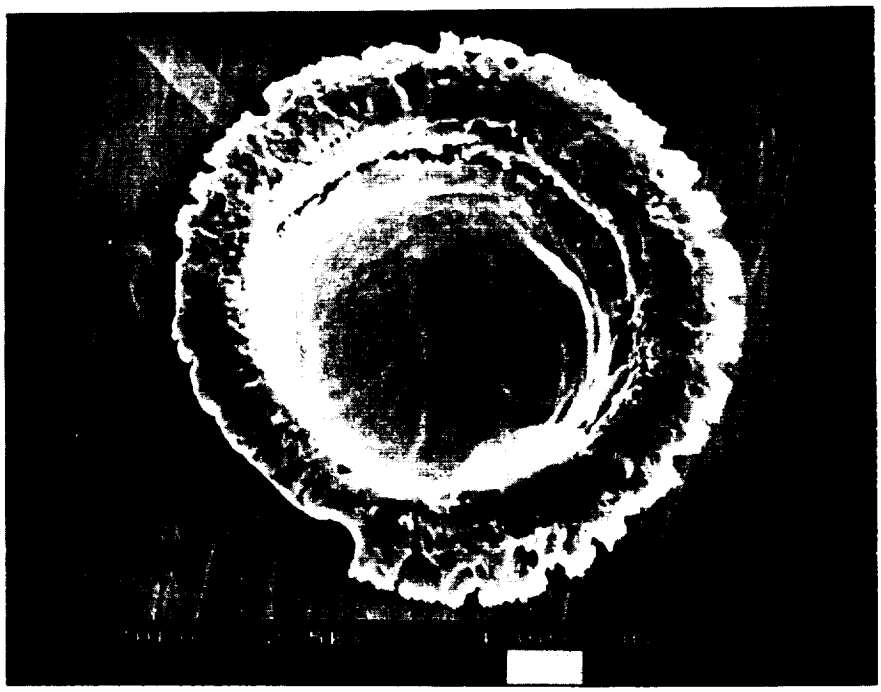

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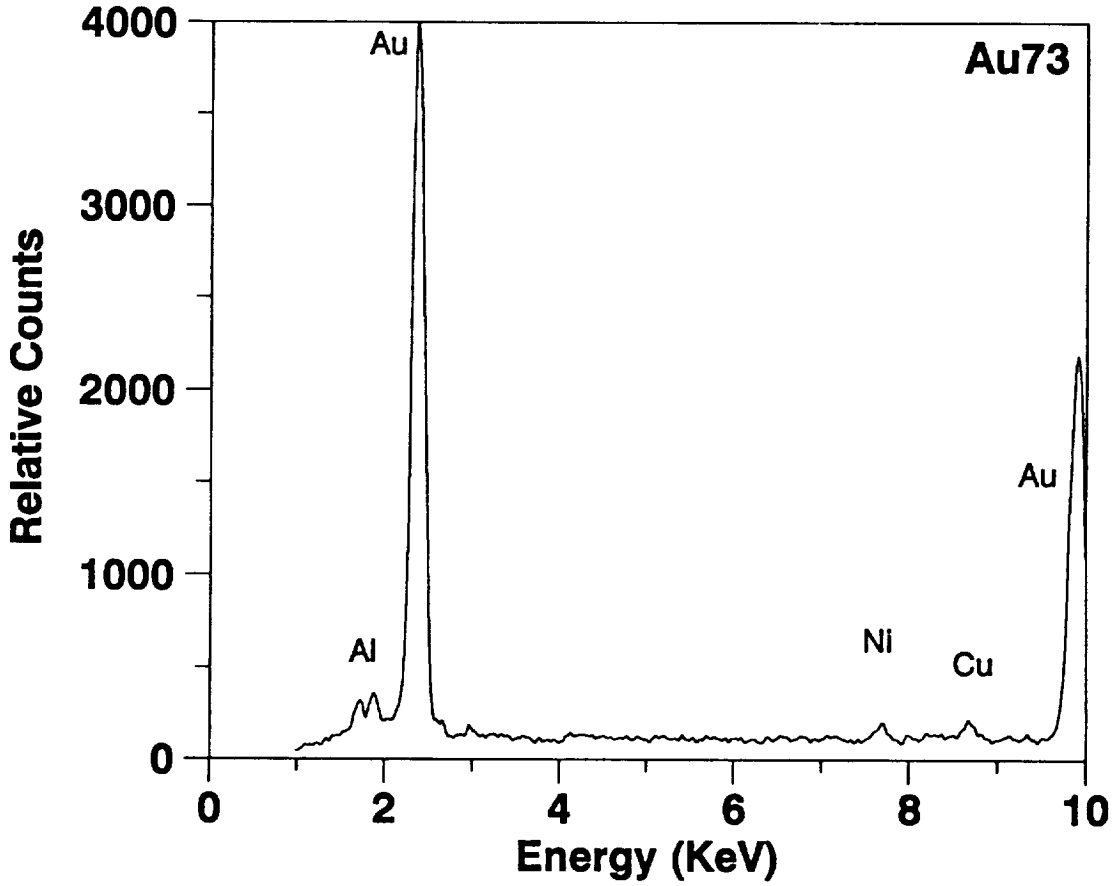

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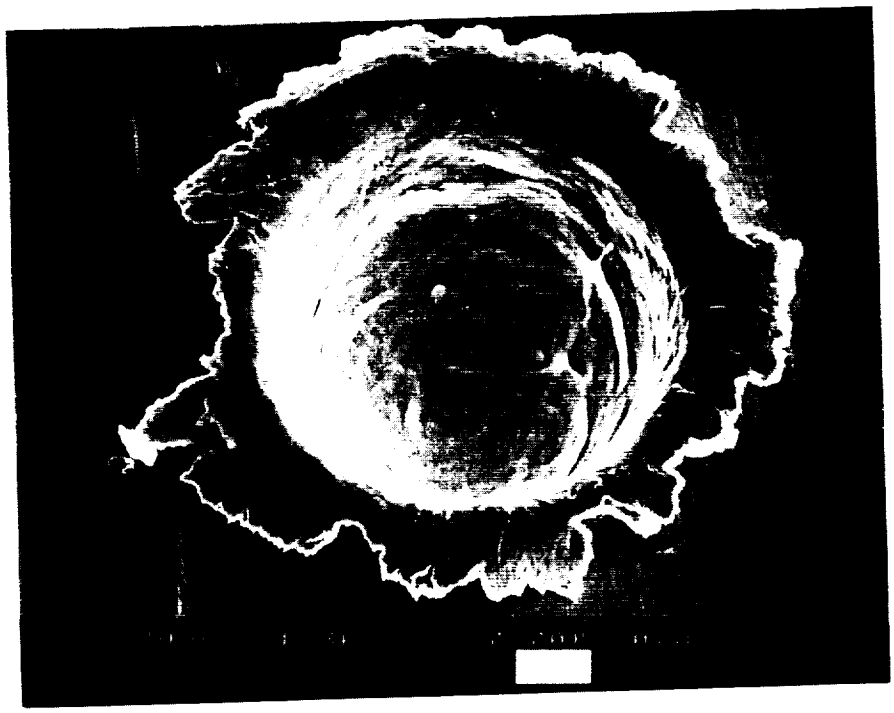

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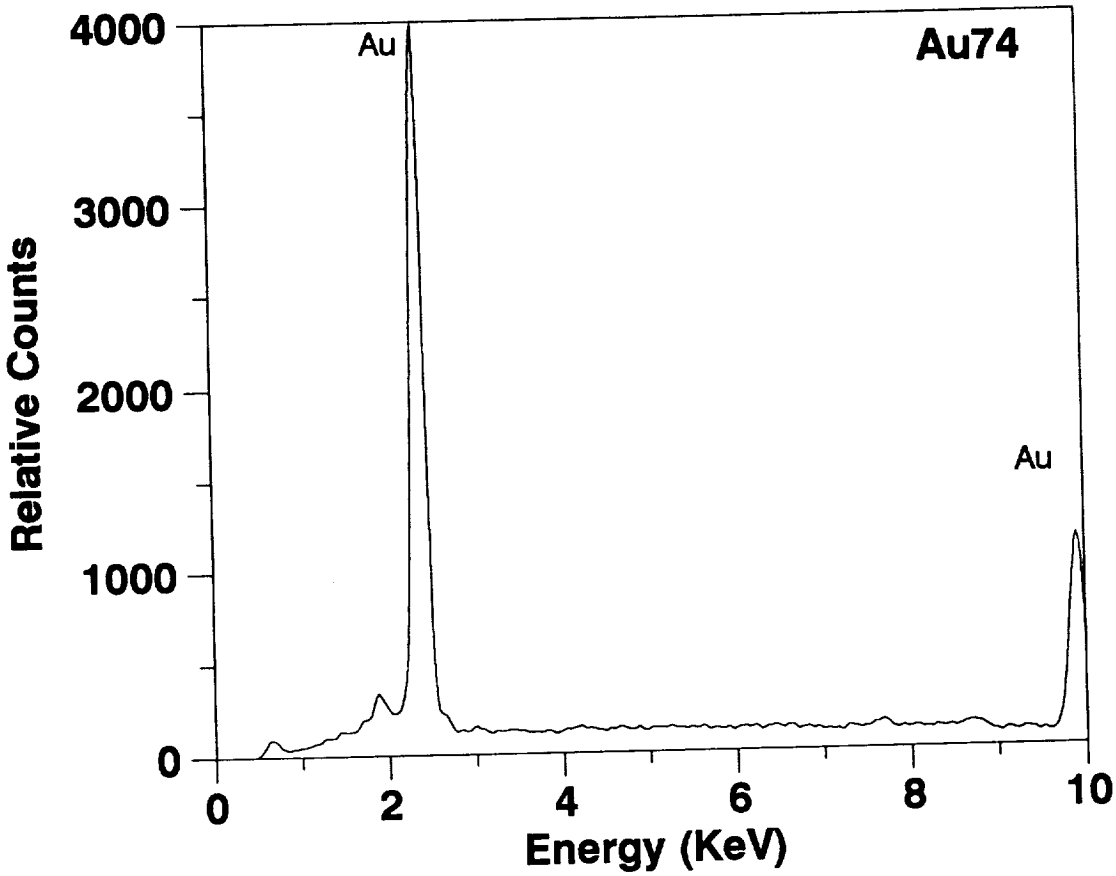

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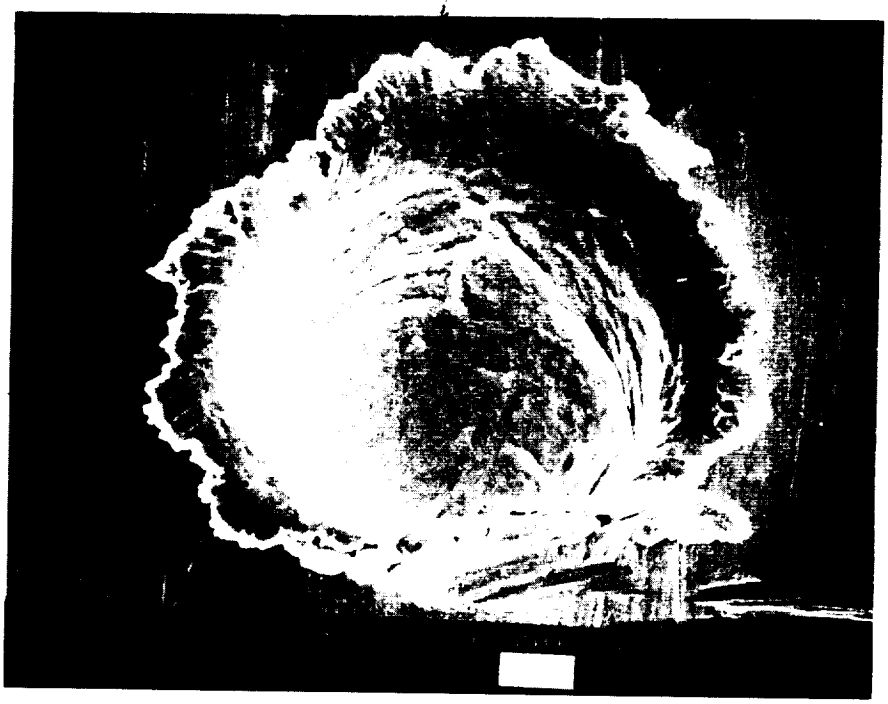

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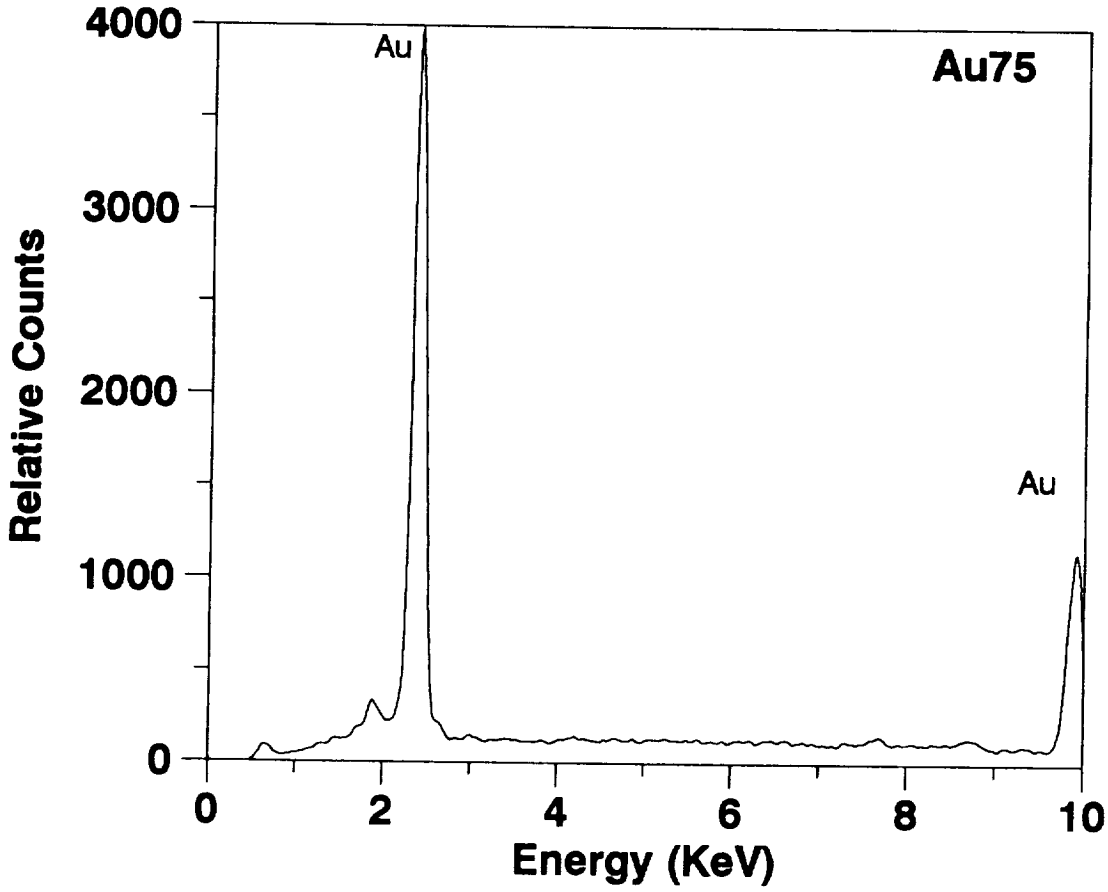

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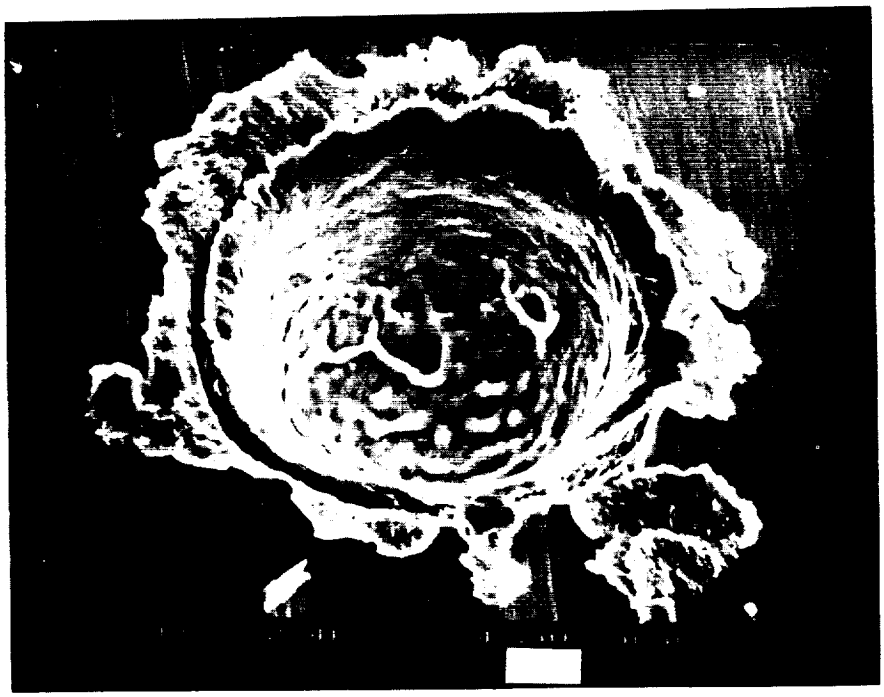

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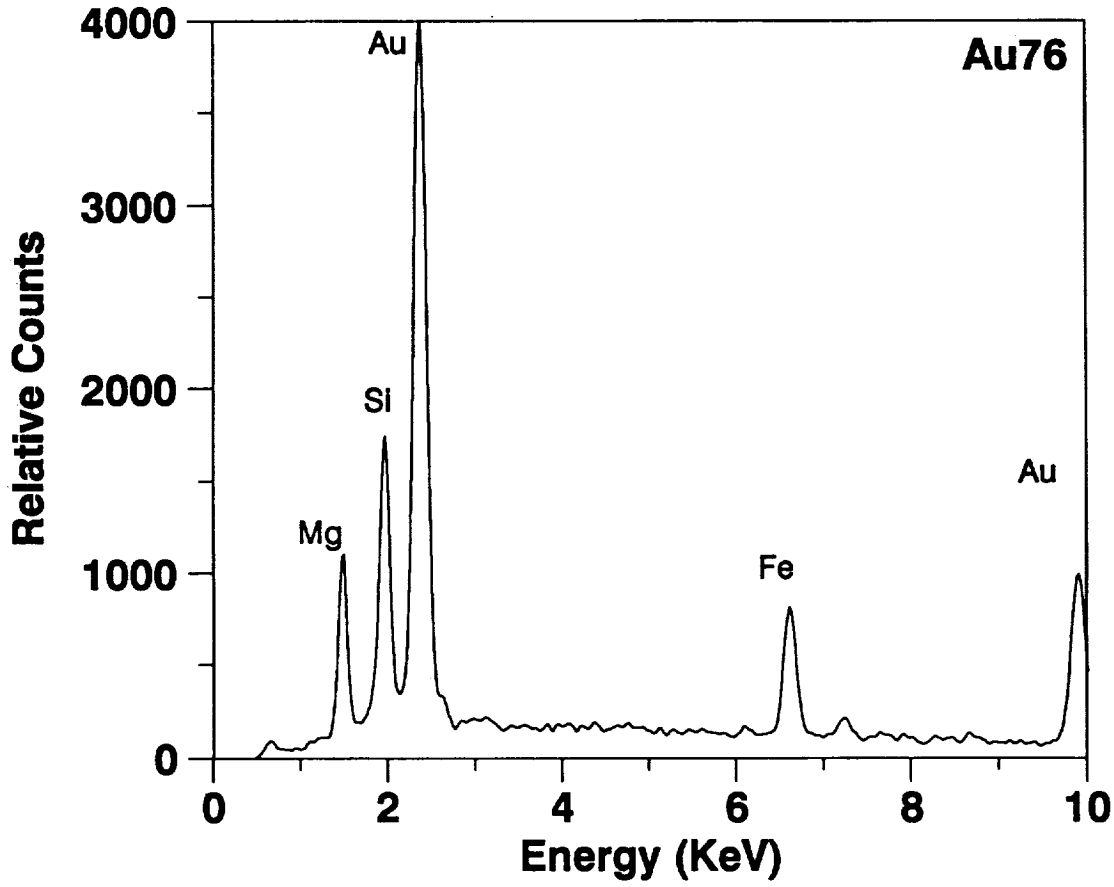

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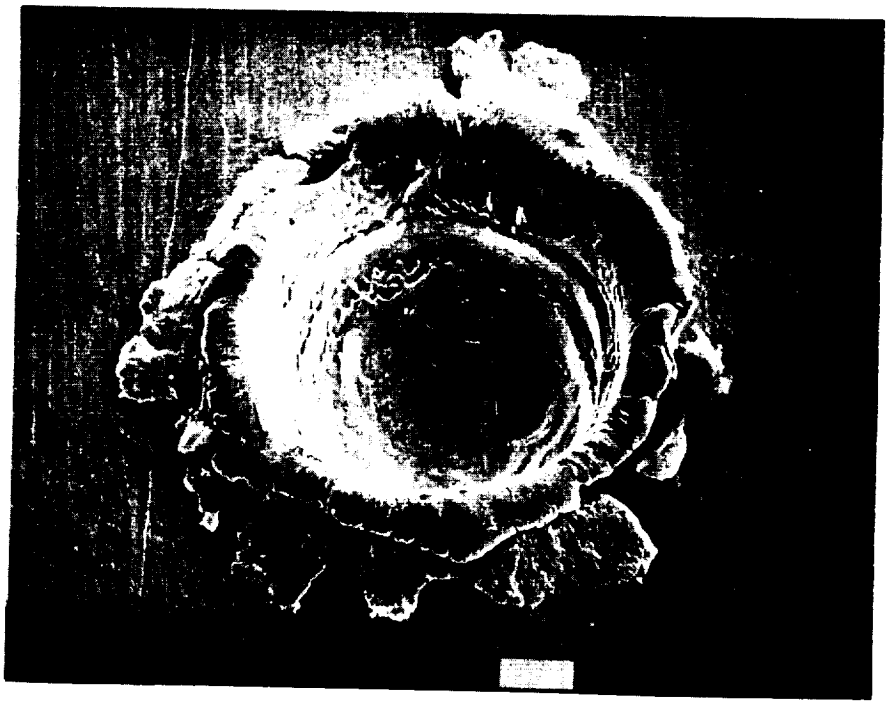

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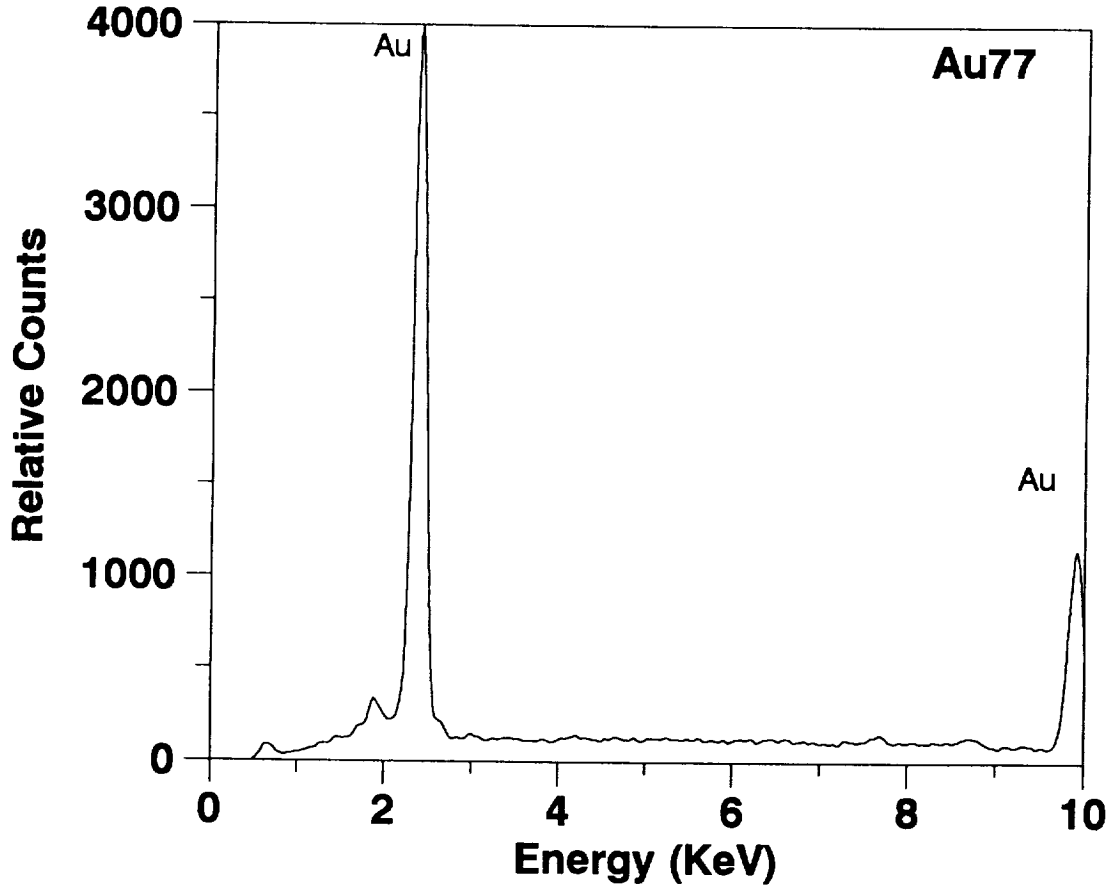

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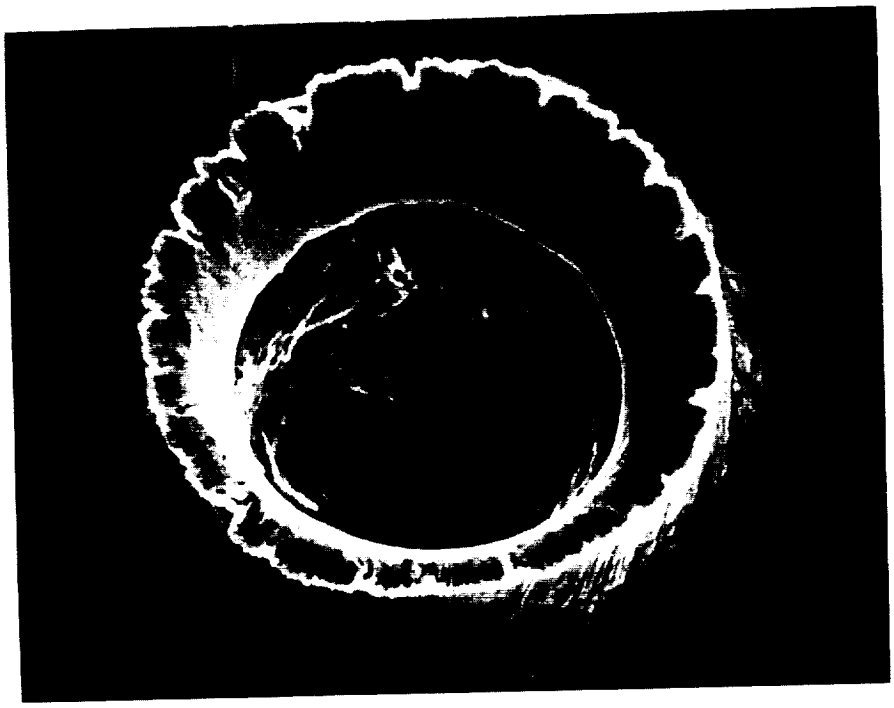

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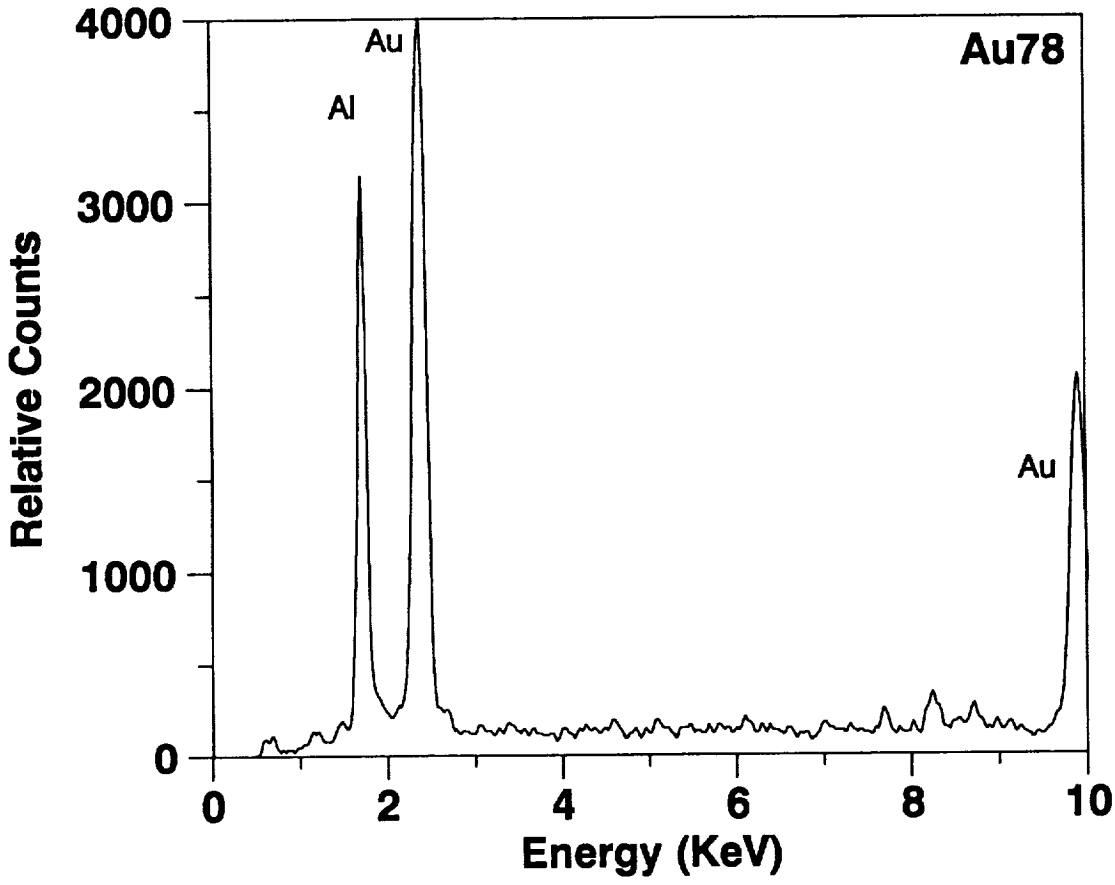

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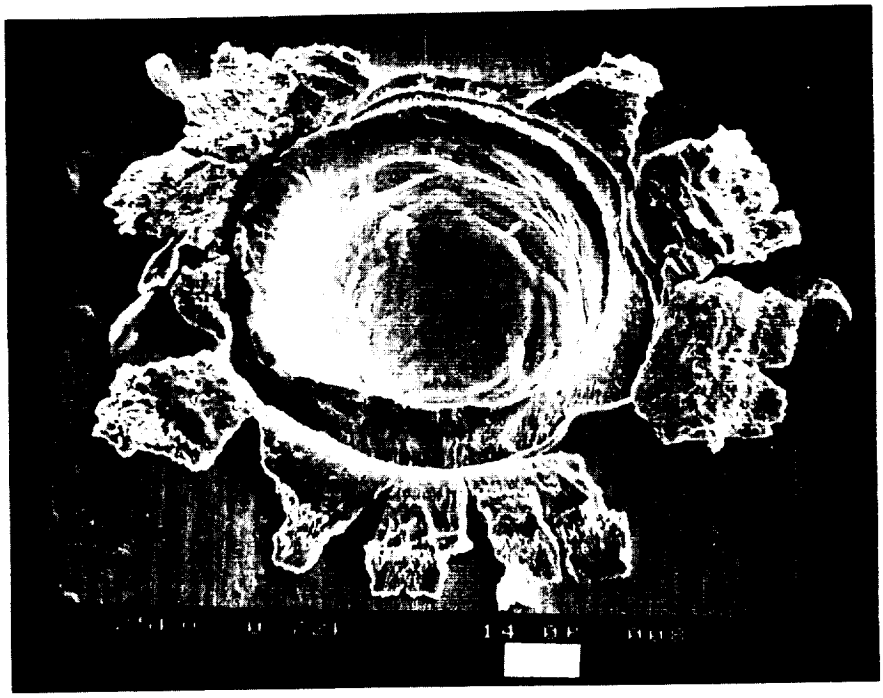

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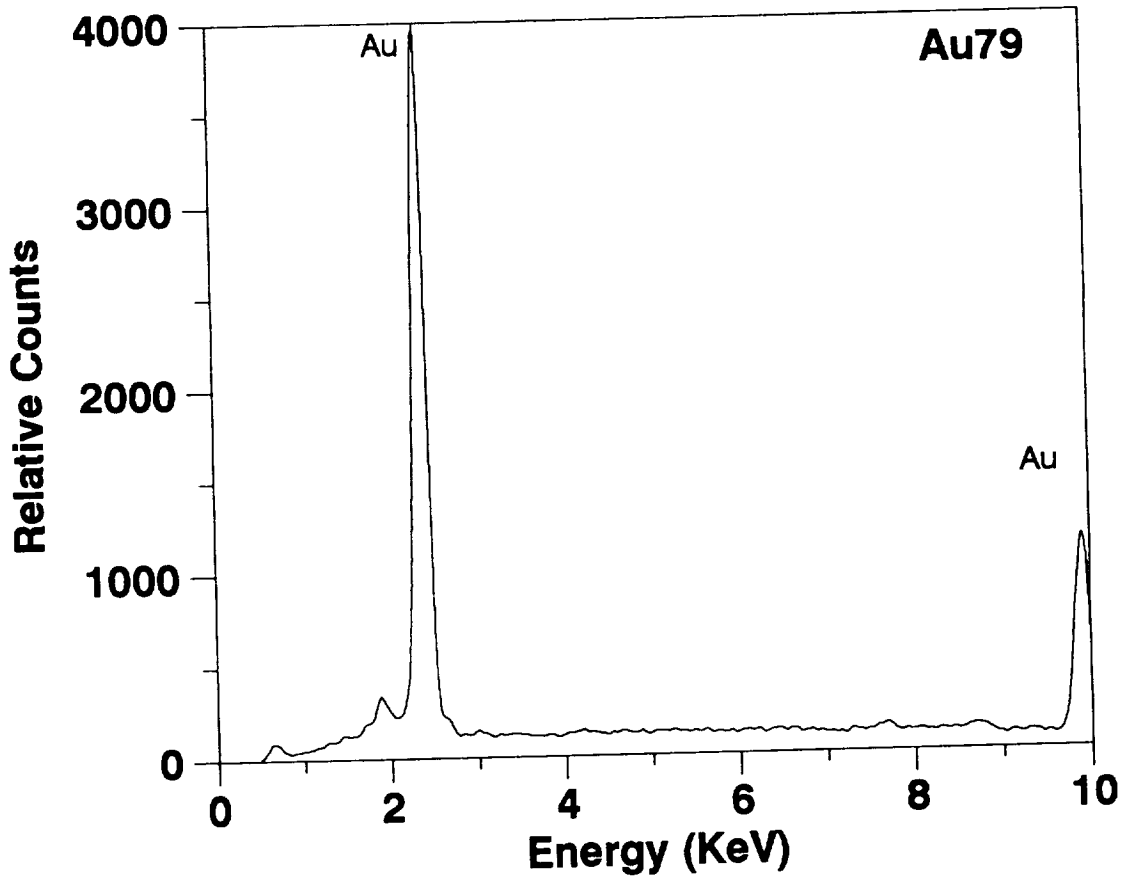

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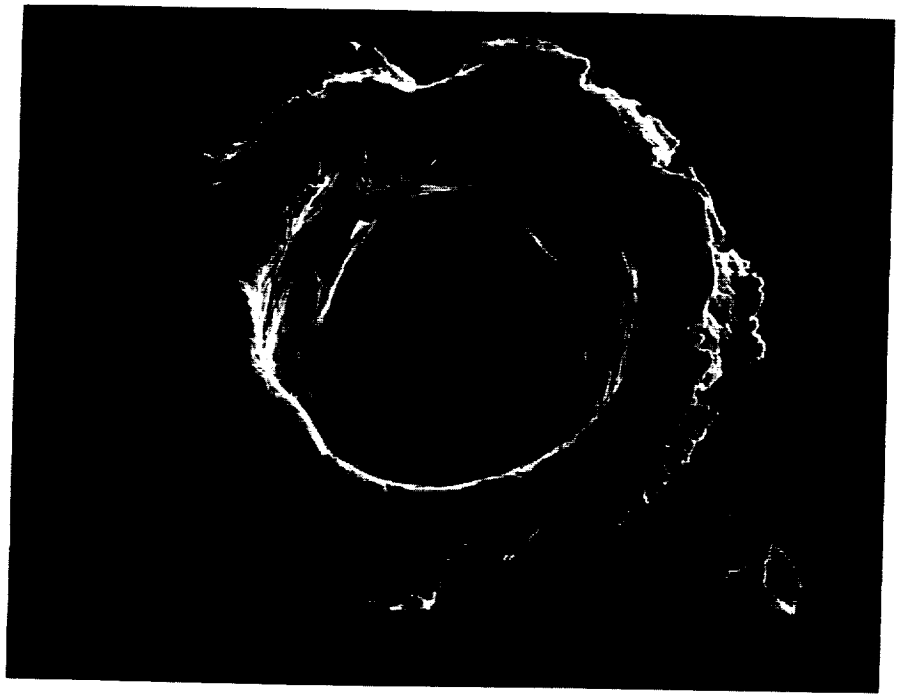

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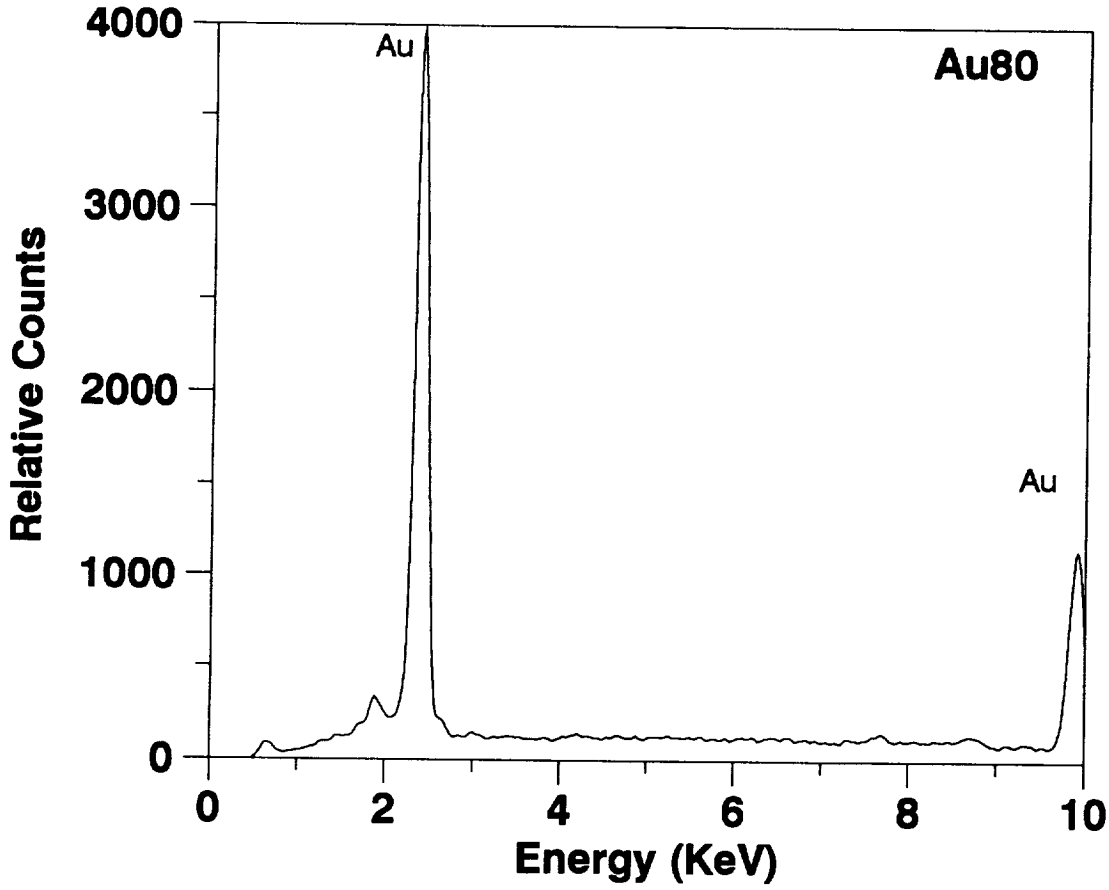

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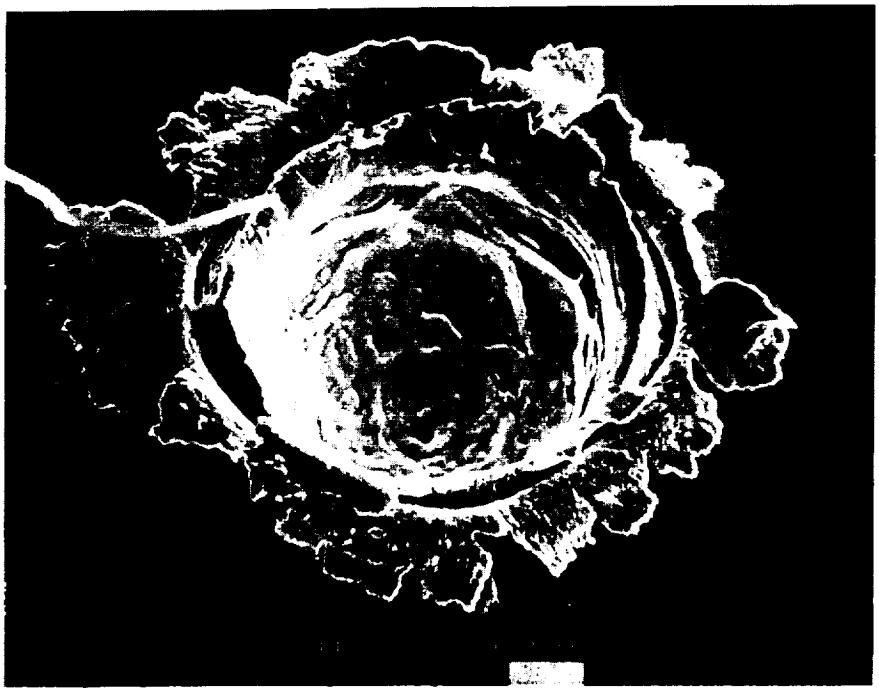

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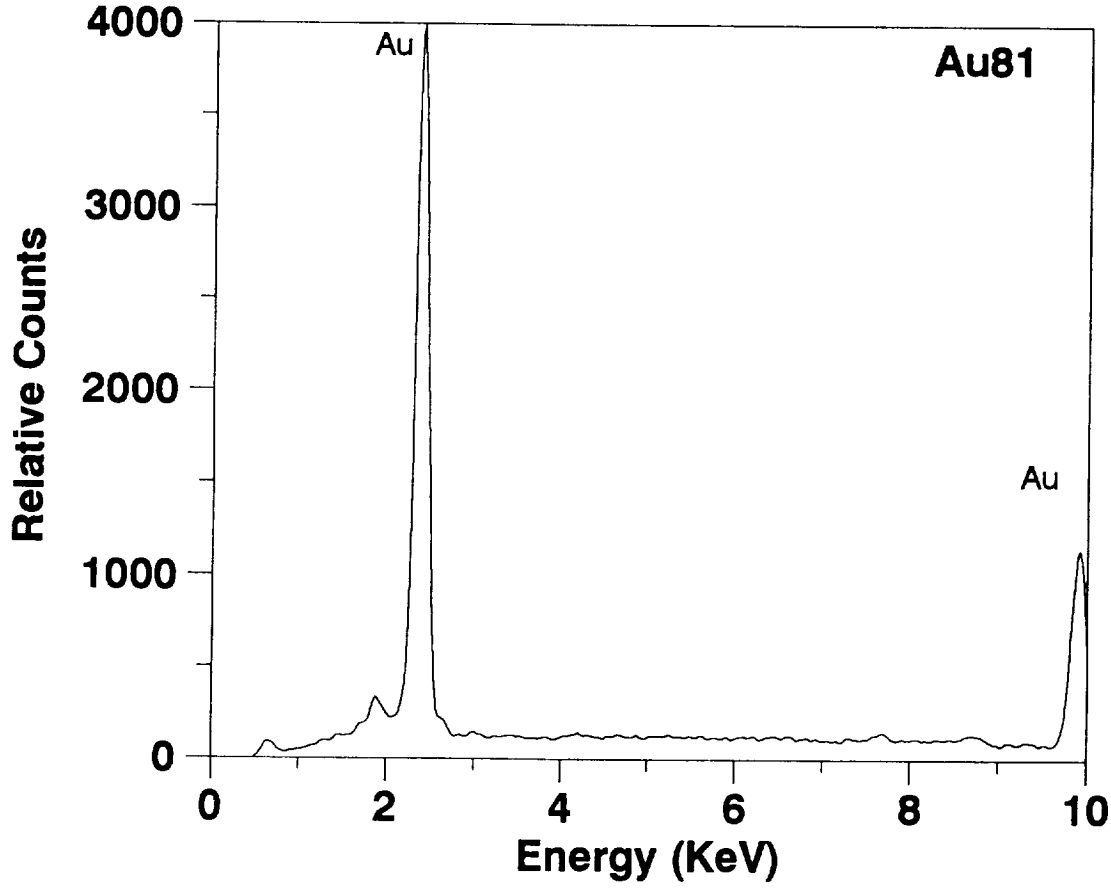

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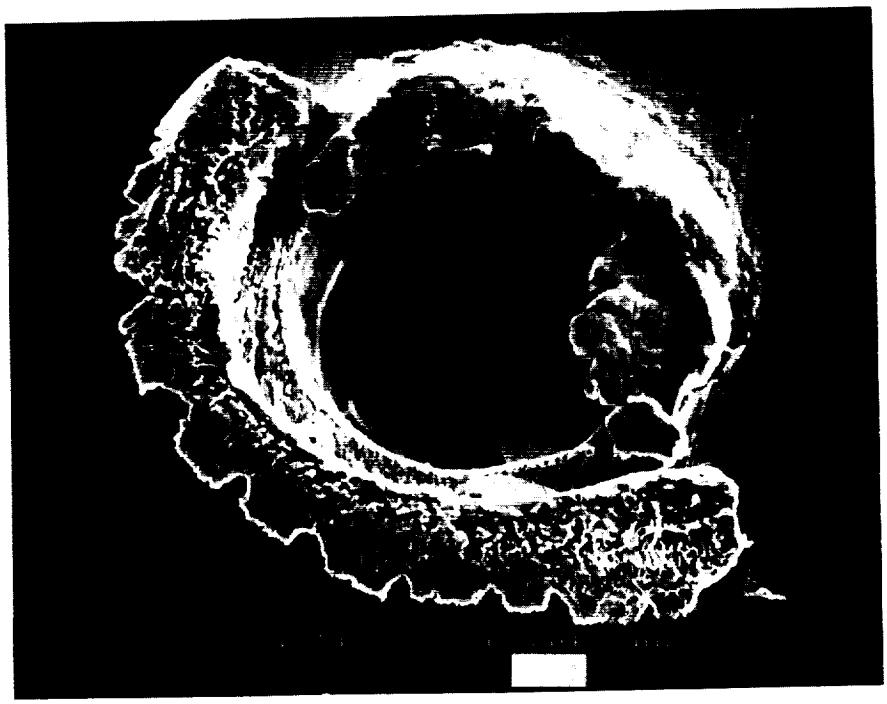

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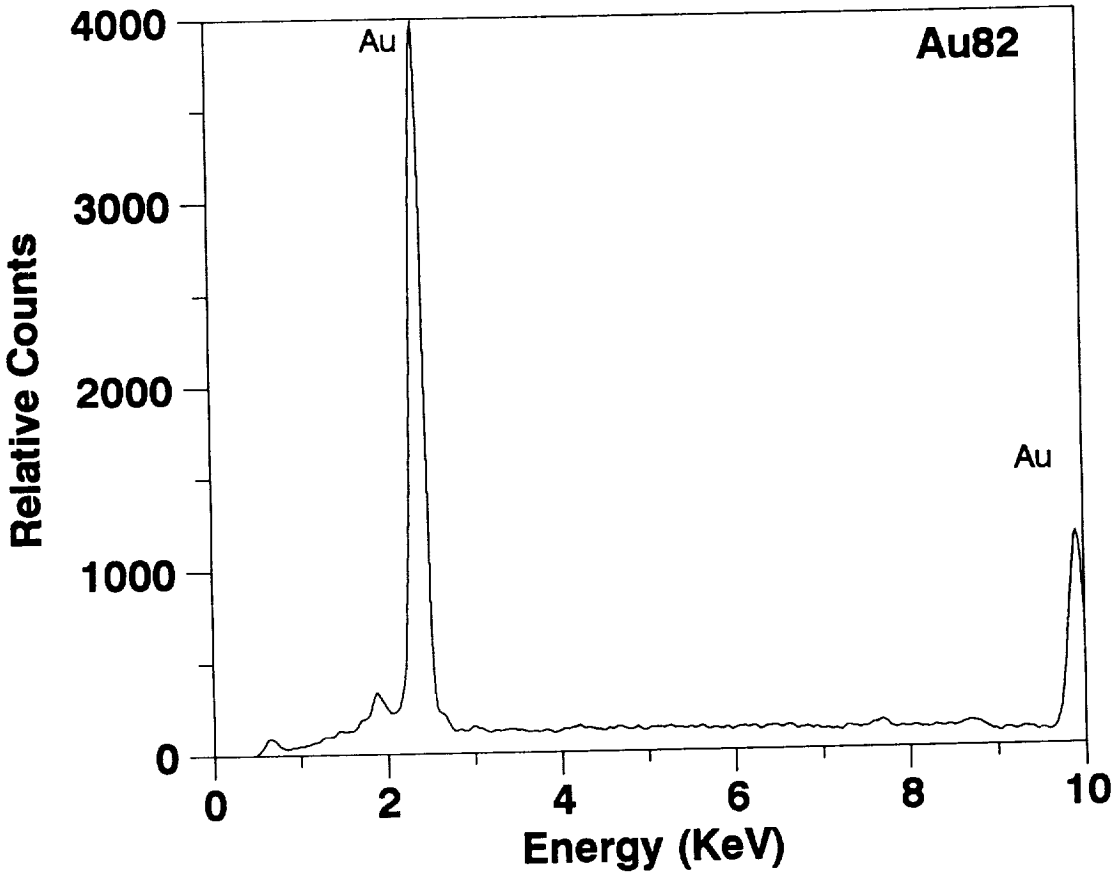

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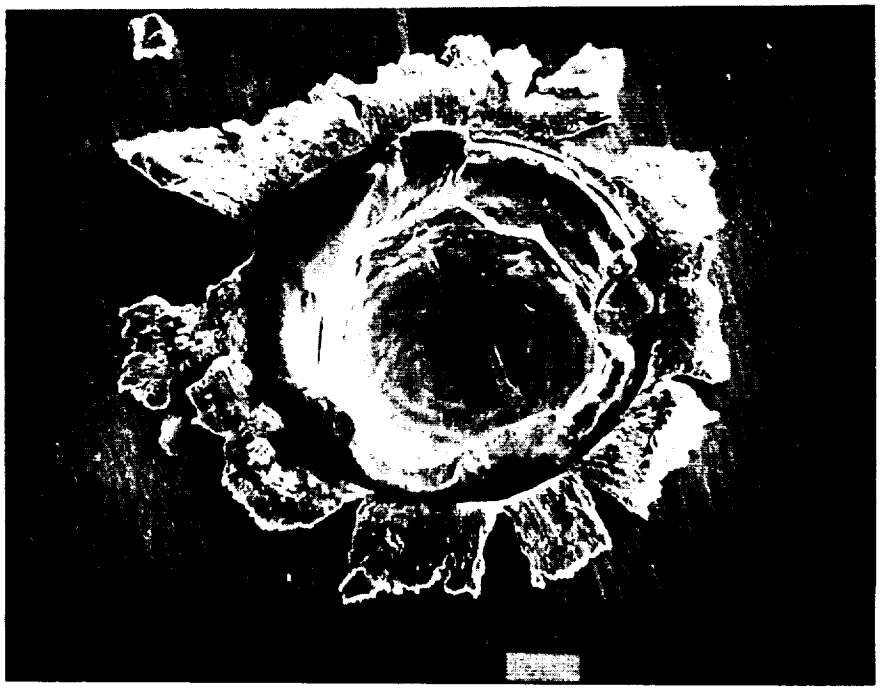
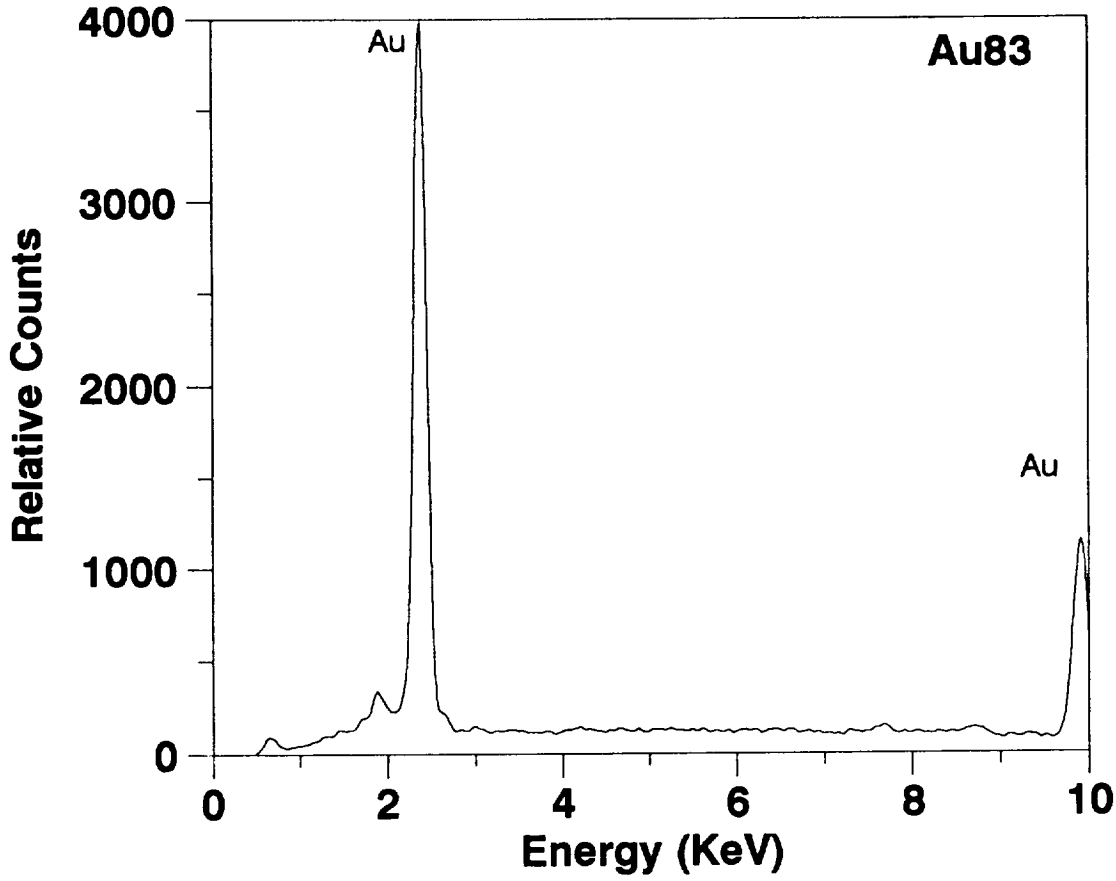


COMPONENT: EOOE
FEATURE: 83
CORE: LD-47

DIAMETER: 75 μm
ORIGIN: Unknown



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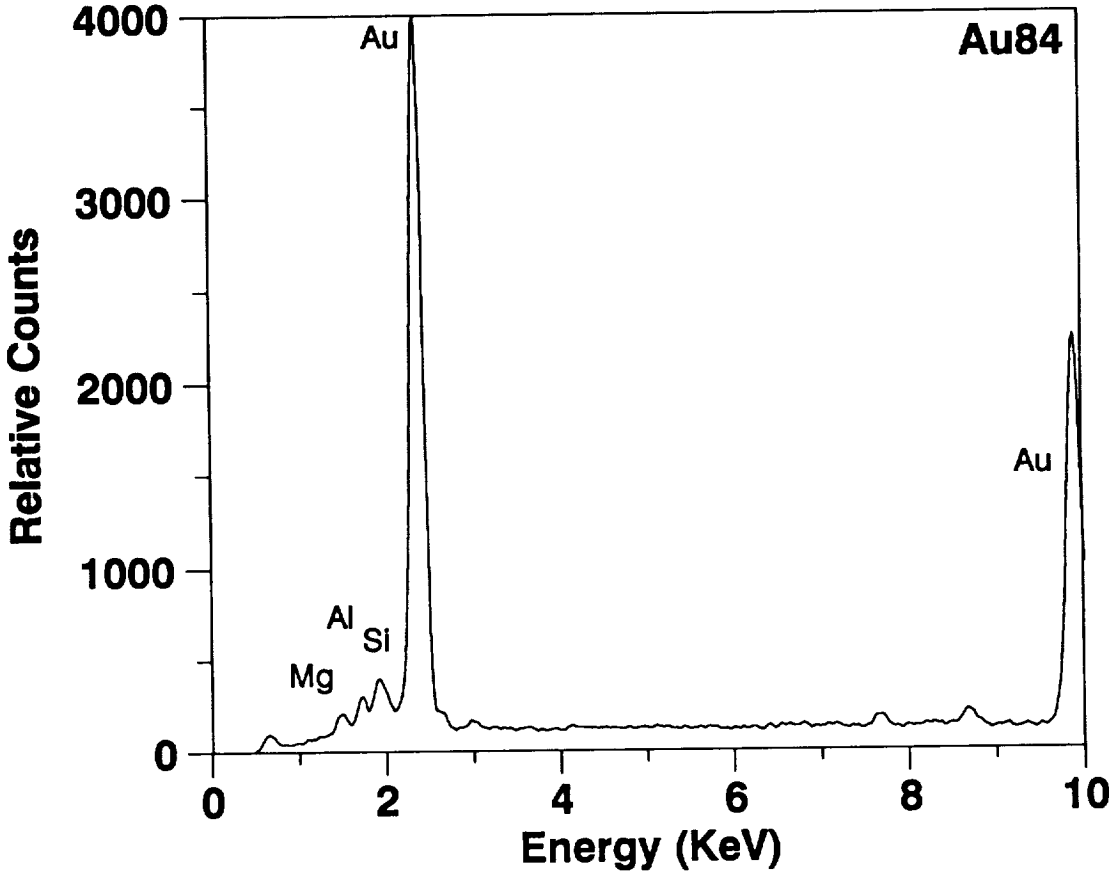
COMPONENT: EOOE
FEATURE: 84
CORE: LD-39

DIAMETER: 65 μm
ORIGIN: Natural



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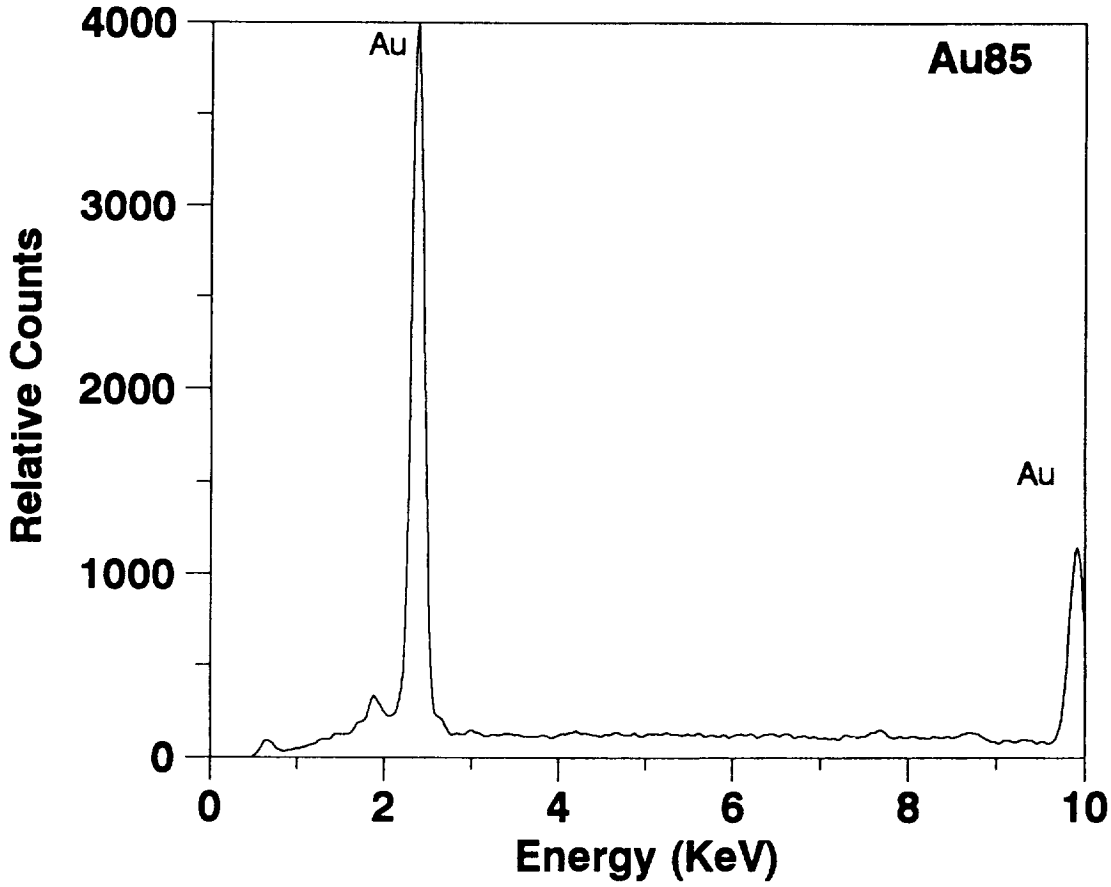
COMPONENT: EOOE
FEATURE: 85
CORE: LD-43

DIAMETER: 155 μm
ORIGIN: Unknown



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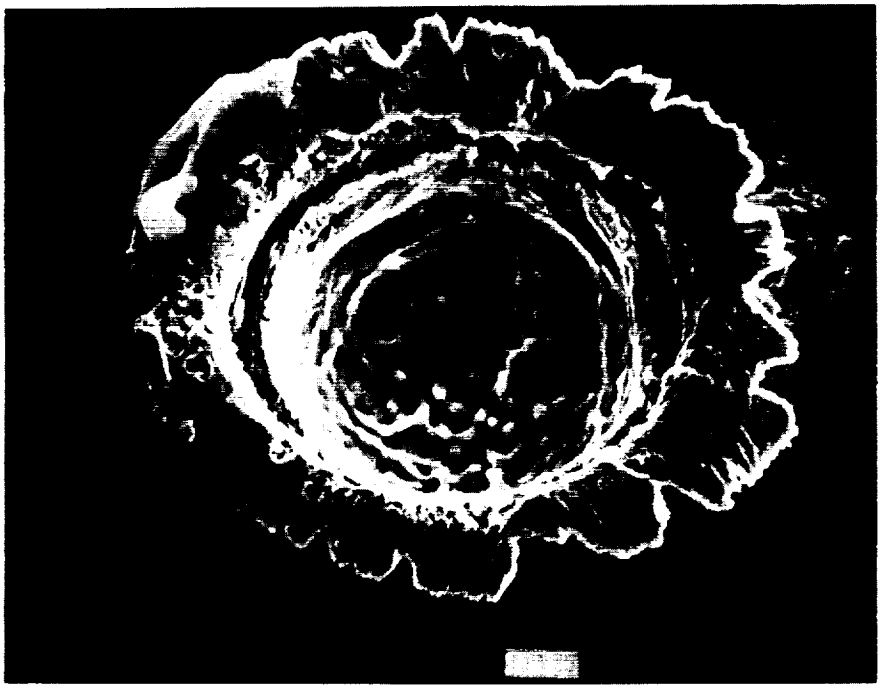
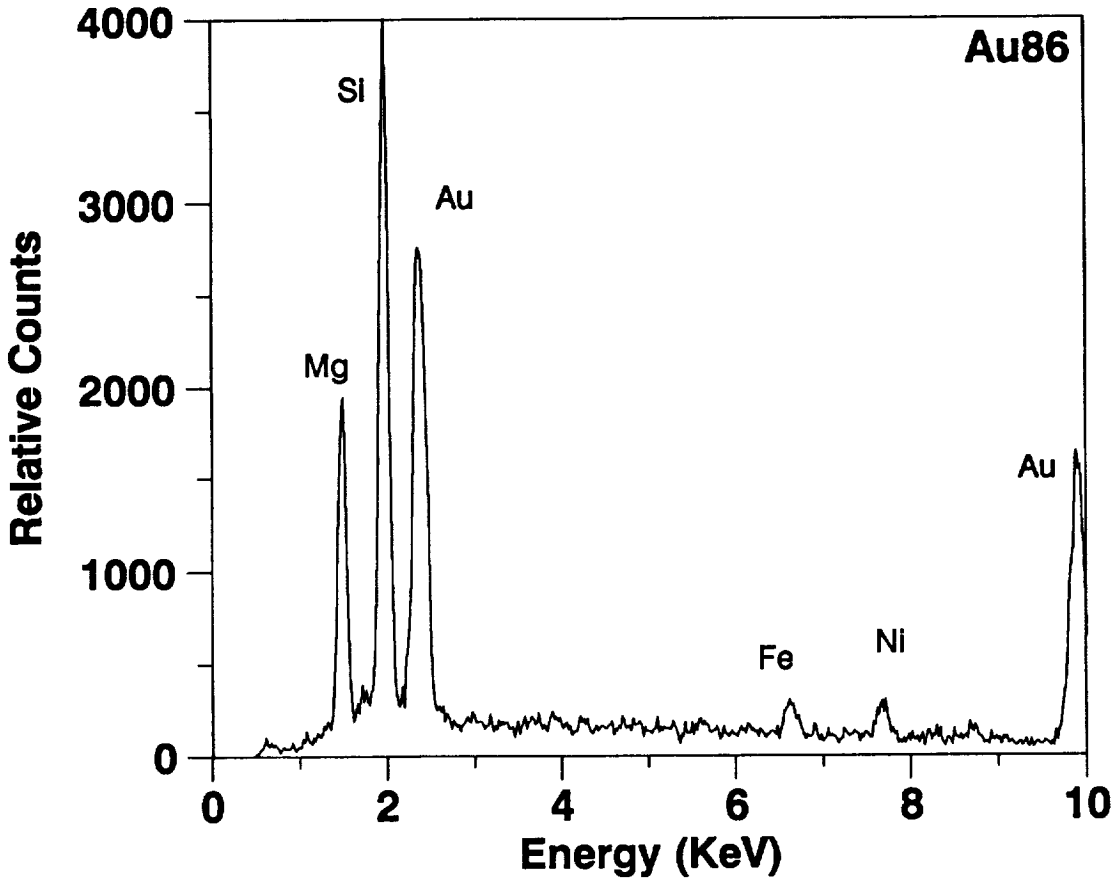


COMPONENT: EOOE
FEATURE: 86
CORE: LD-41

DIAMETER: 25 μm
ORIGIN: Natural



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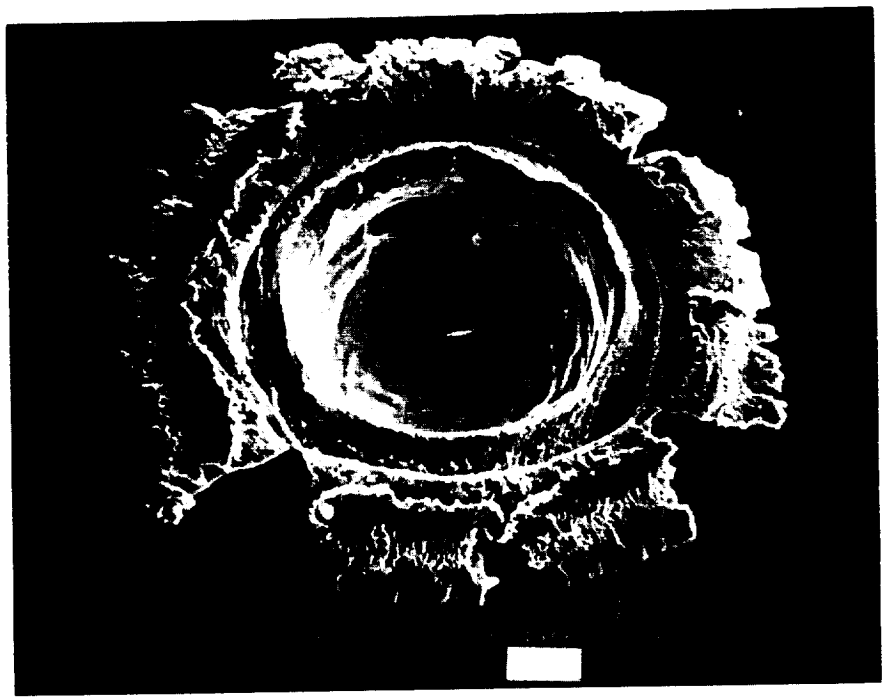
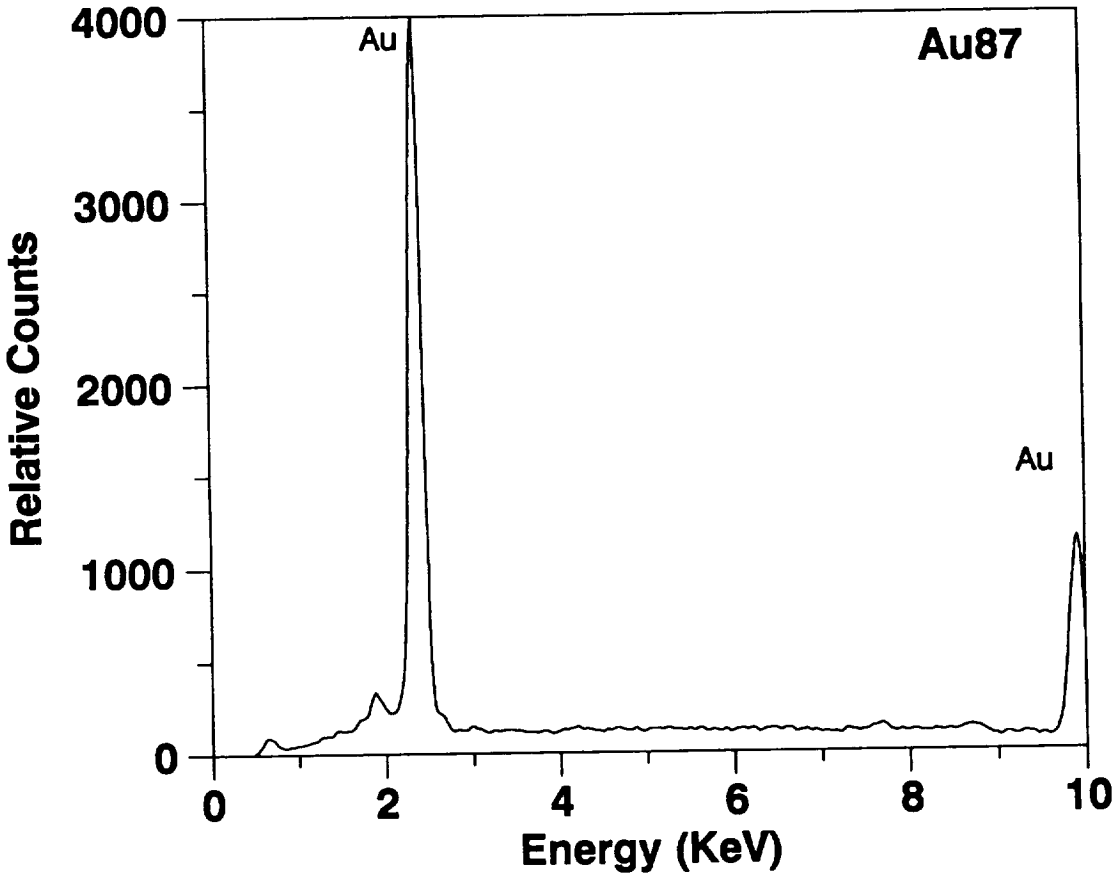


COMPONENT: EOOE
FEATURE: 87
CORE: LD-21

DIAMETER: 60 μm
ORIGIN: Unknown



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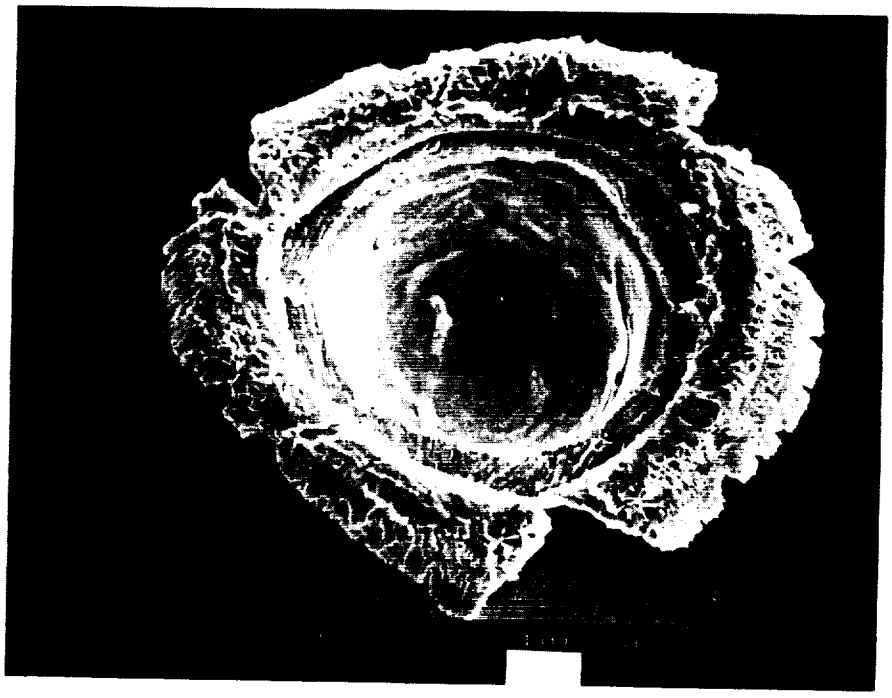
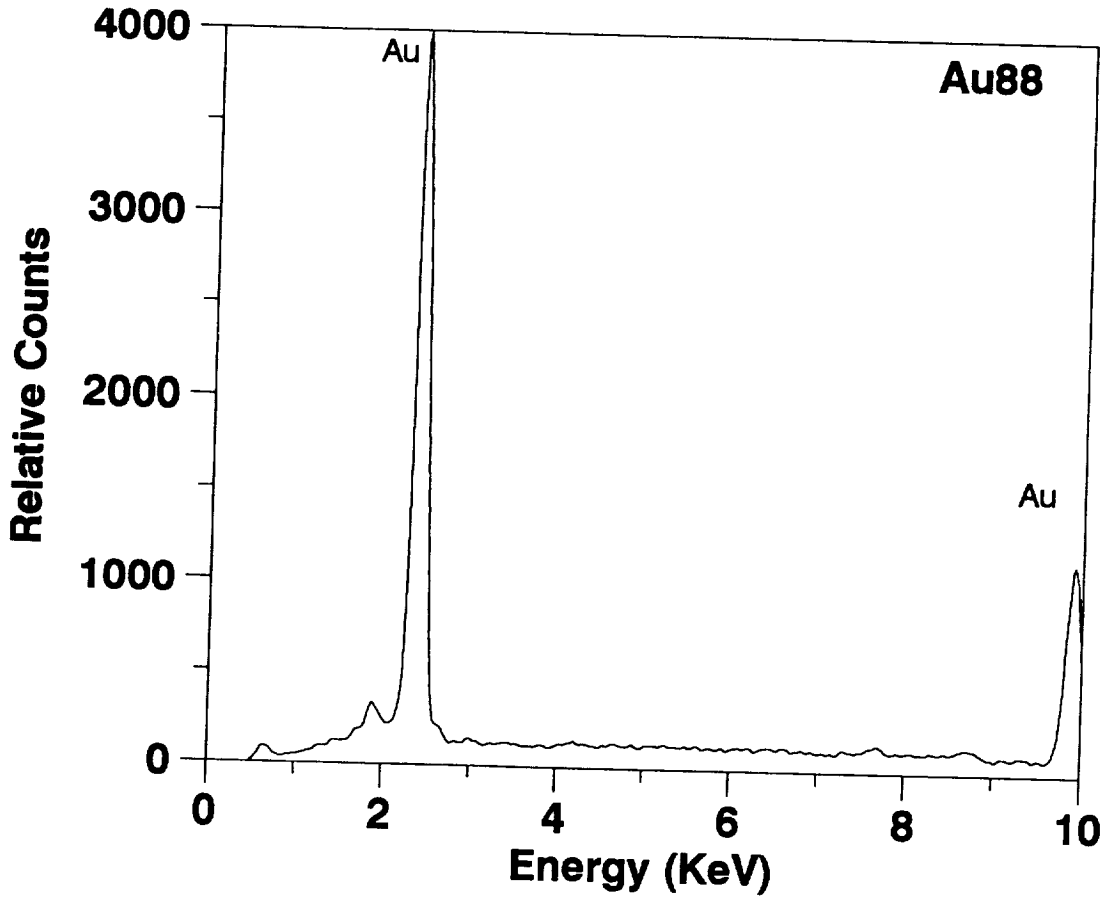


COMPONENT: EOOE
FEATURE: 88
CORE: LD-20

DIAMETER: 40 μm
ORIGIN: Unknown



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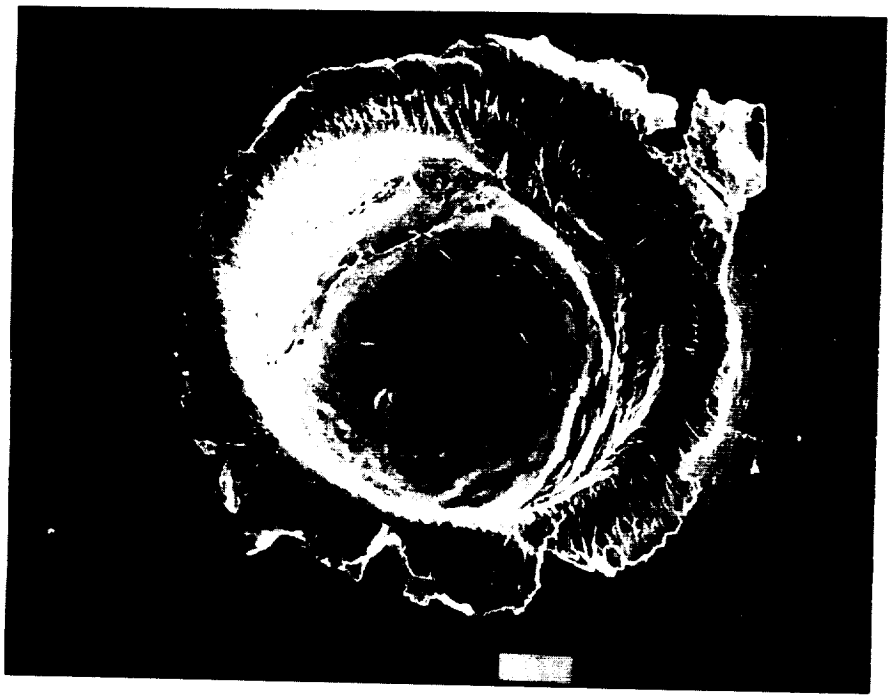
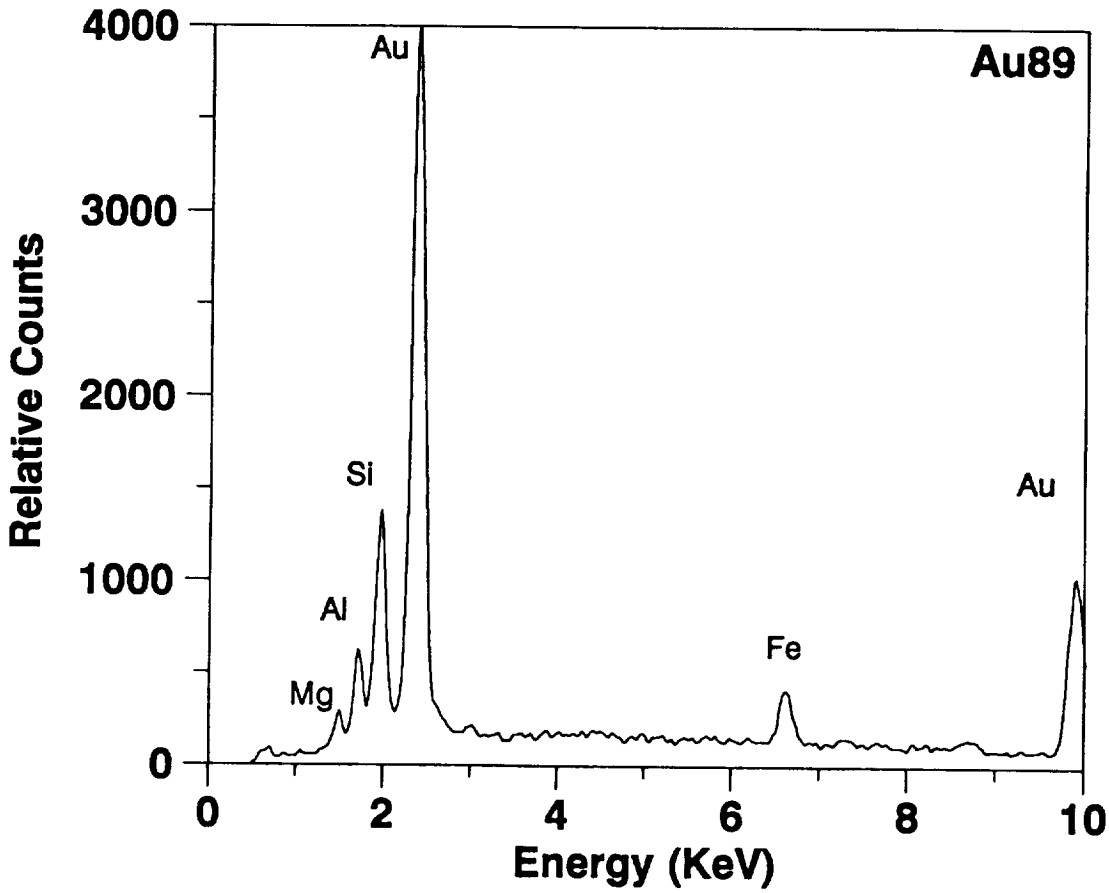


COMPONENT: EOOE
FEATURE: 89
CORE: LD-23

DIAMETER: 155 μm
ORIGIN: Natural



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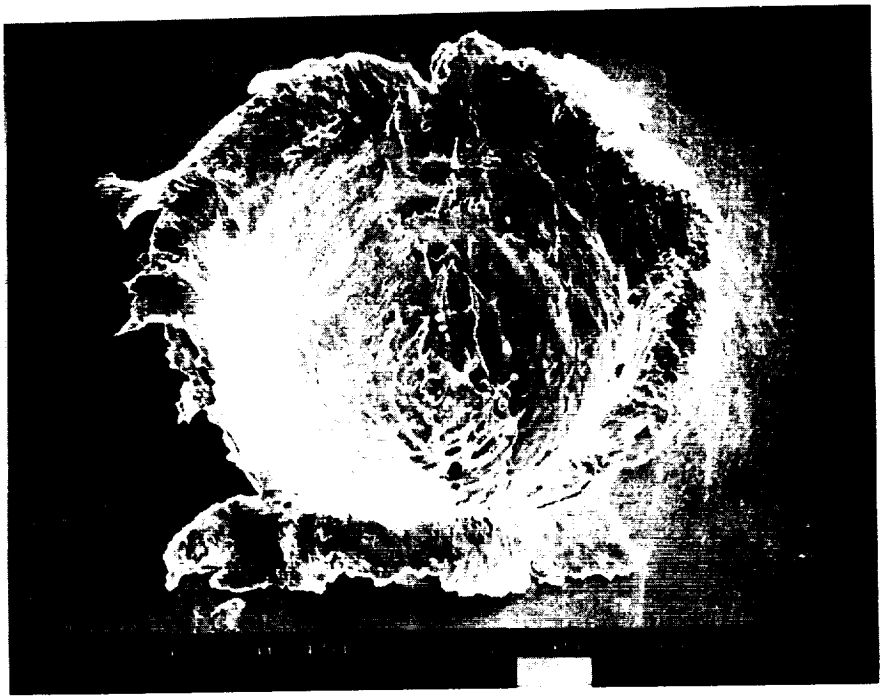
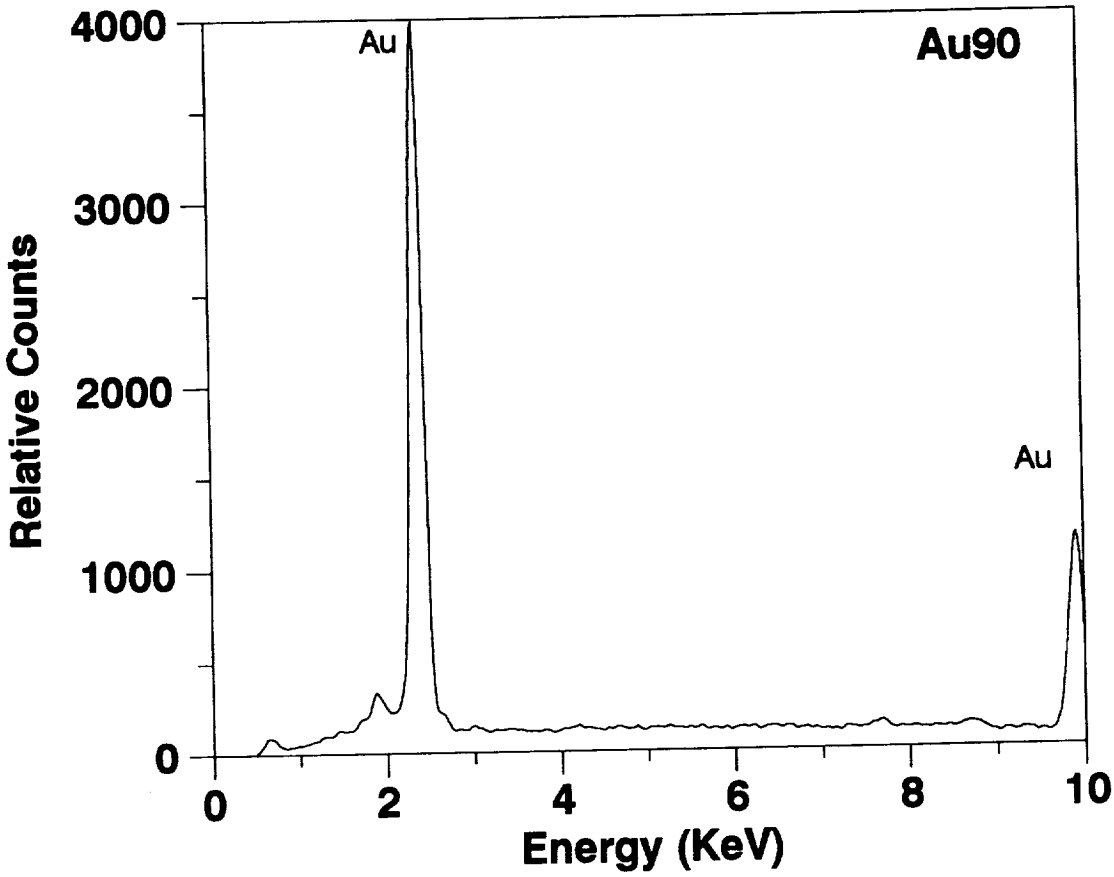


COMPONENT: EOOE
FEATURE: 90
CORE: LD-25

DIAMETER: 160 μm
ORIGIN: Unknown



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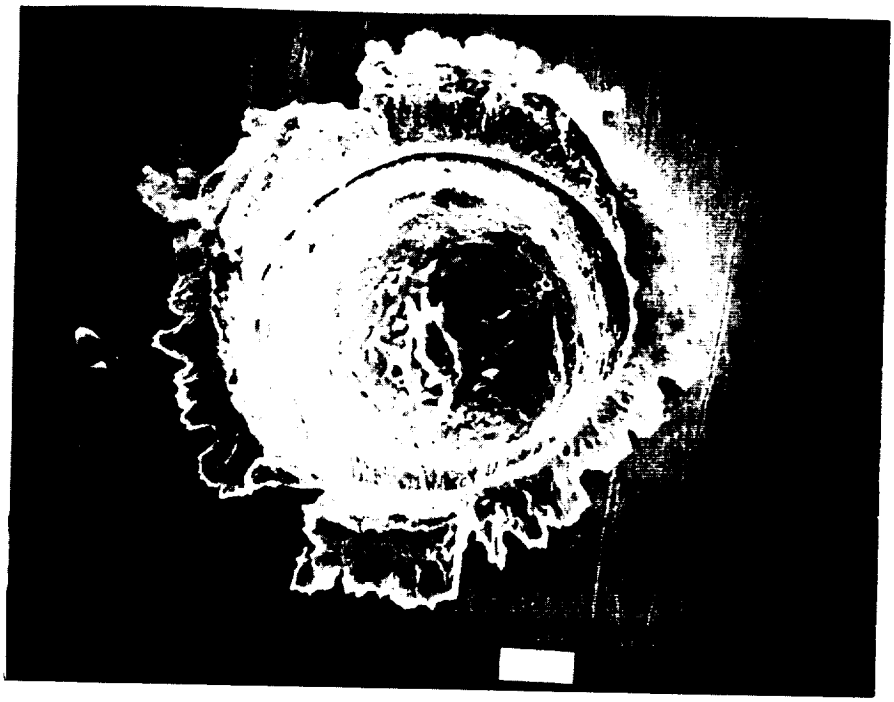
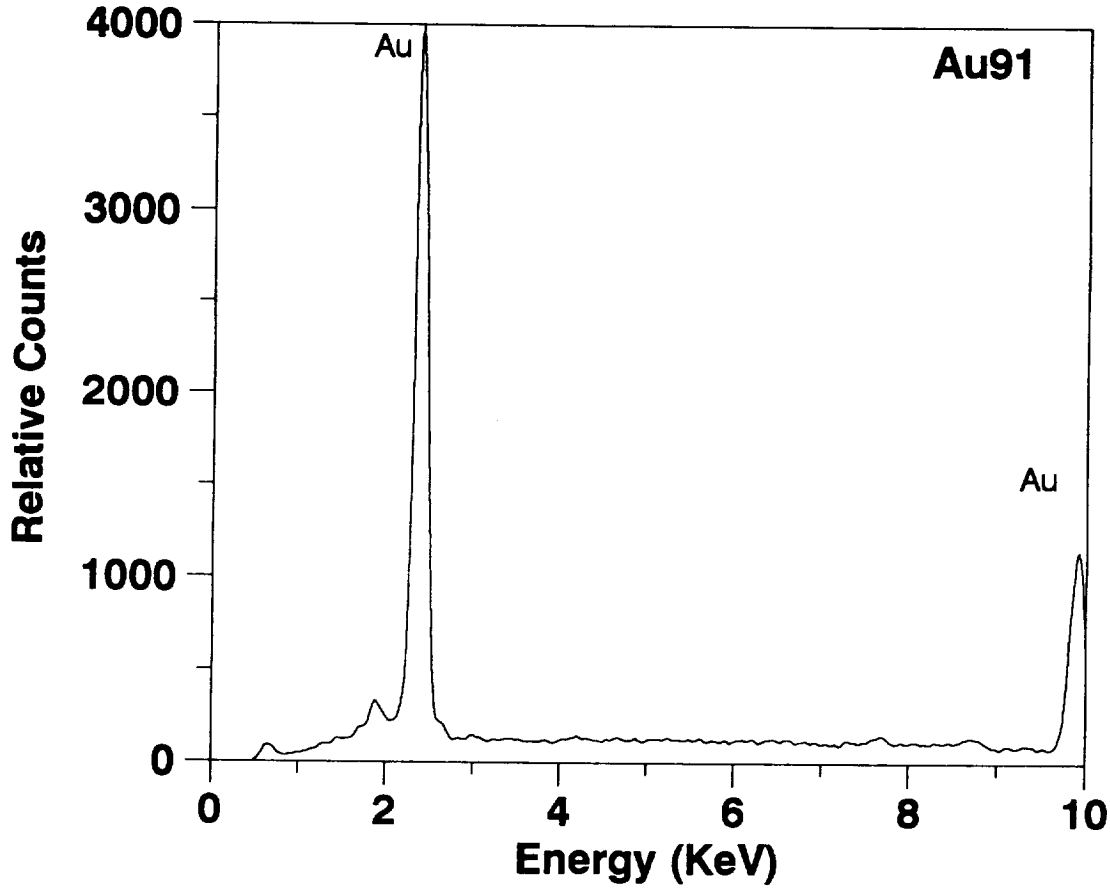


COMPONENT: EOOE
FEATURE: 91
CORE: LD-24

DIAMETER: 55 μm
ORIGIN: Unknown



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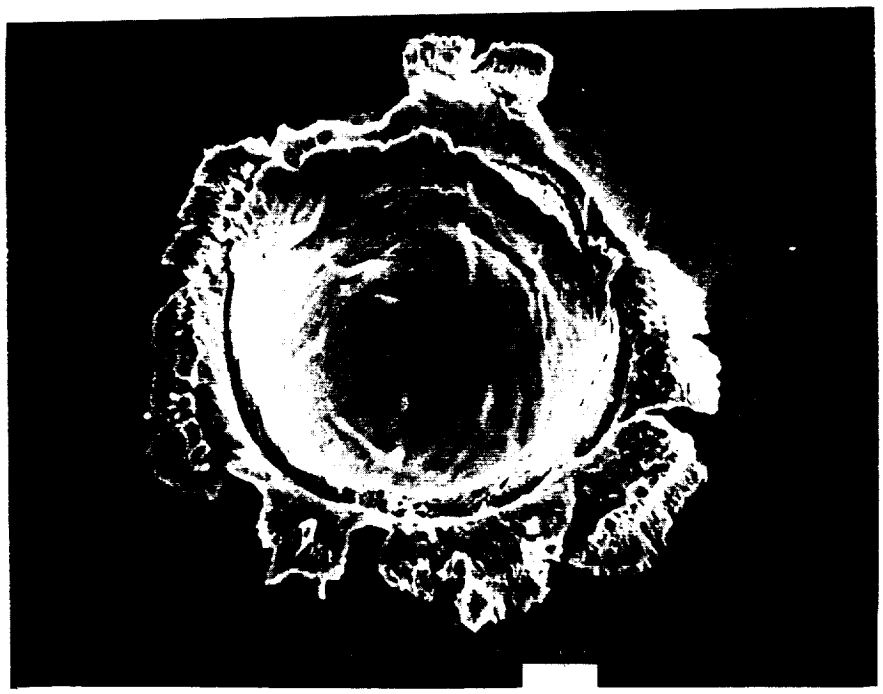
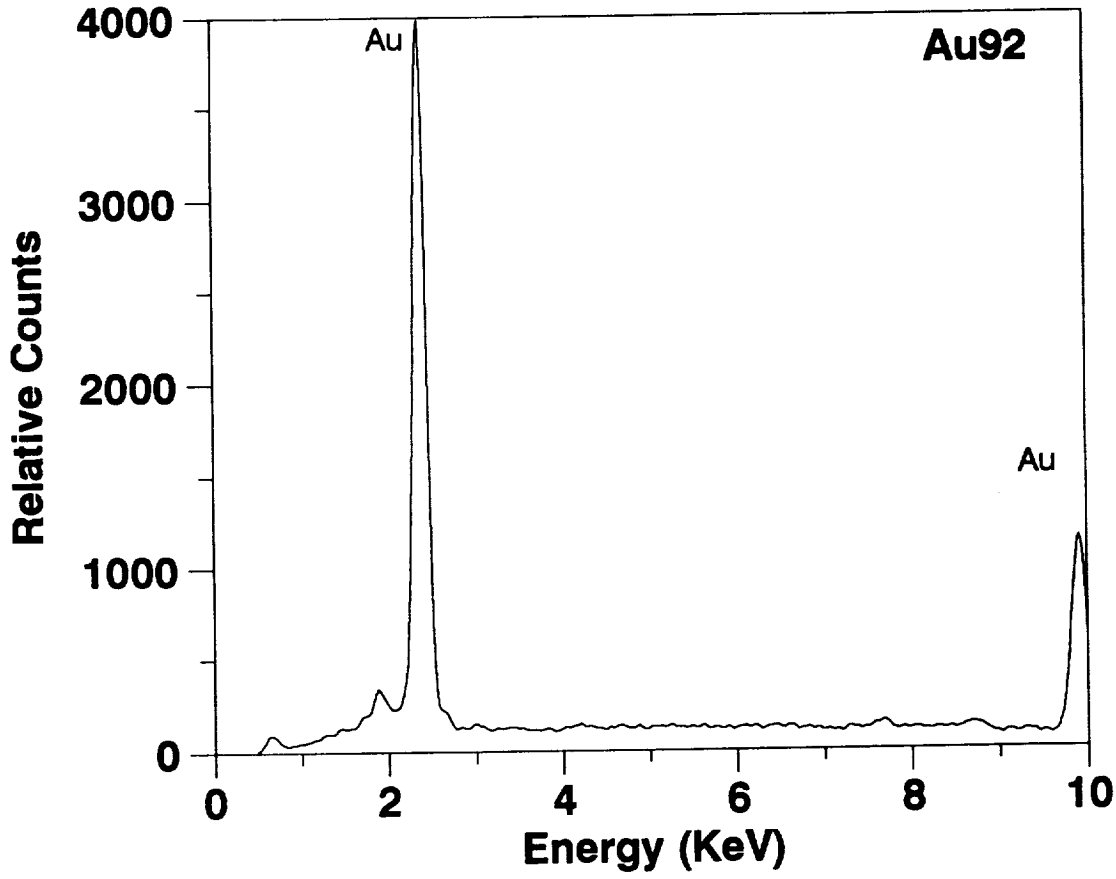


COMPONENT: EOOE
FEATURE: 92
CORE: LD-37

DIAMETER: 30 μm
ORIGIN: Unknown



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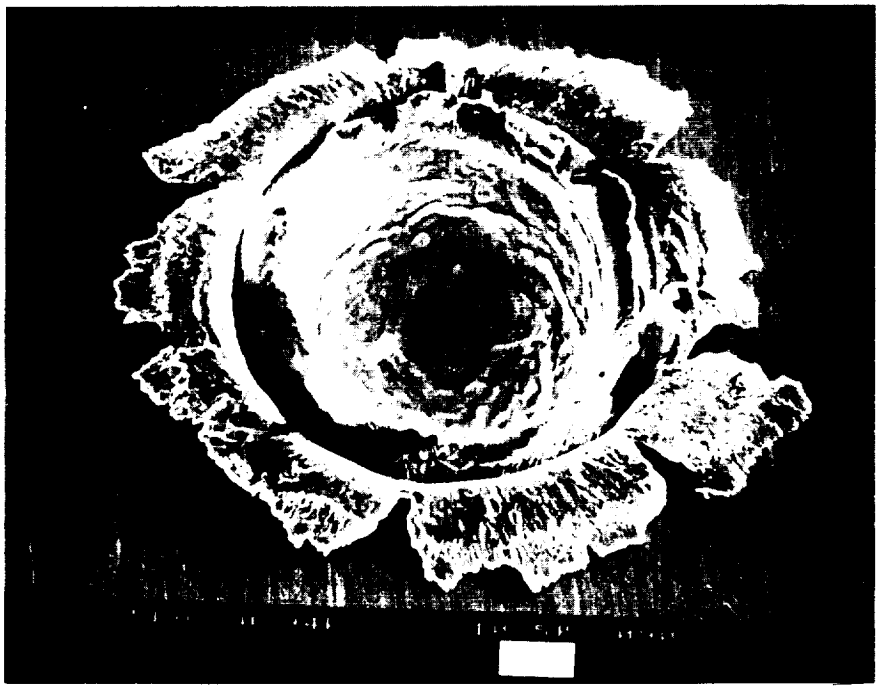
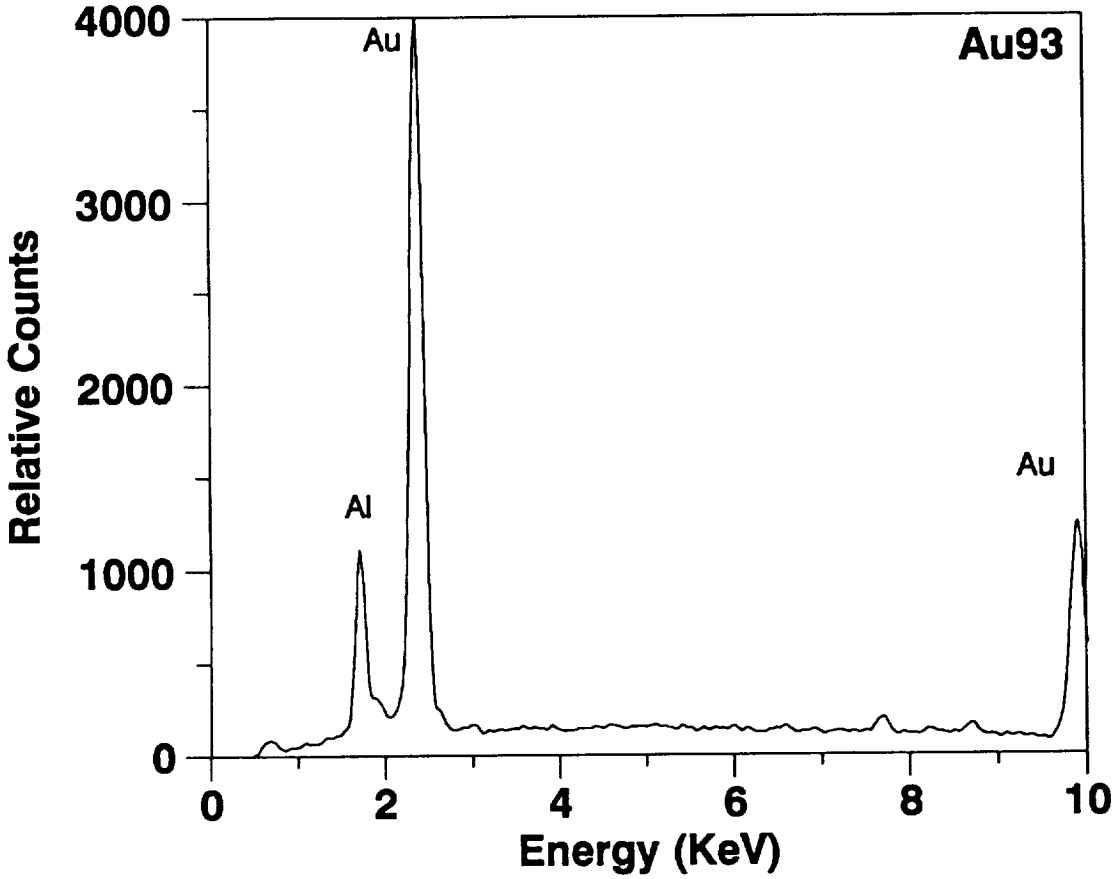


COMPONENT: EOOE
FEATURE: 93
CORE: LD-19

DIAMETER: 60 μm
ORIGIN: Man-made



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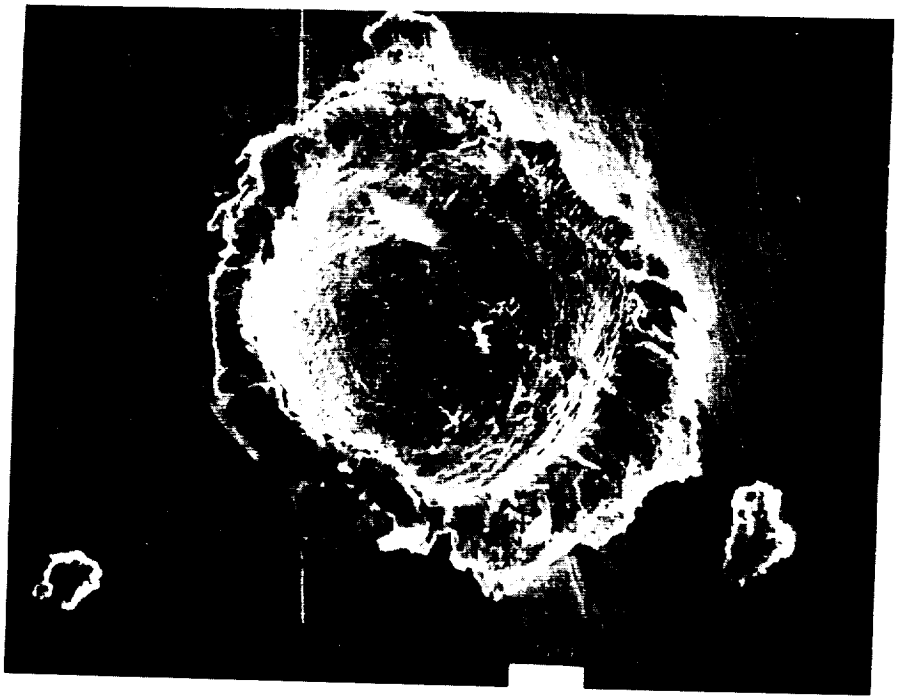
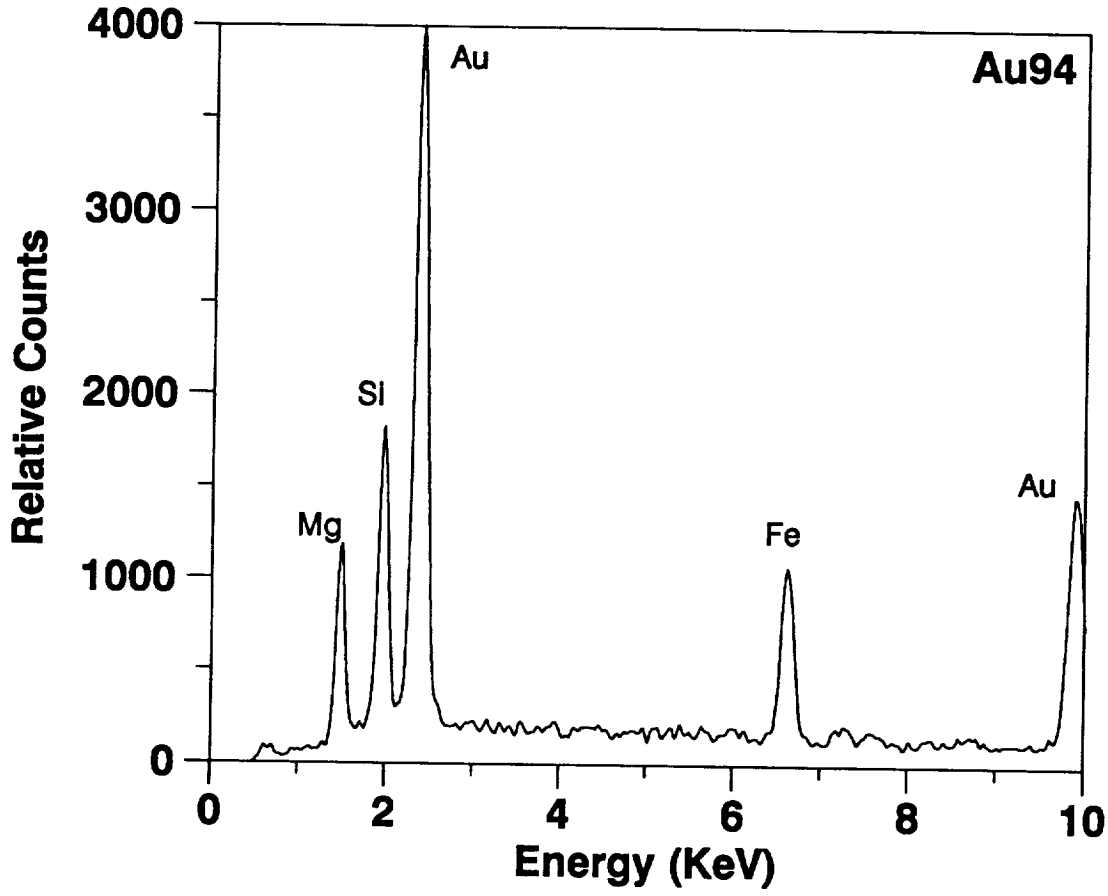


COMPONENT: EOOE
FEATURE: 94
CORE: LD-36

DIAMETER: 35 μm
ORIGIN: Natural



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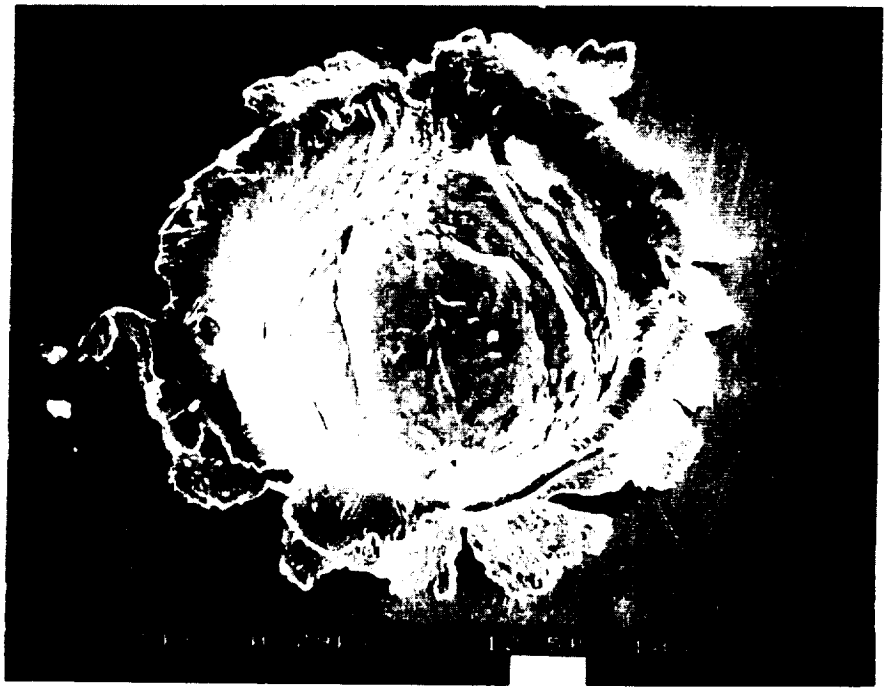
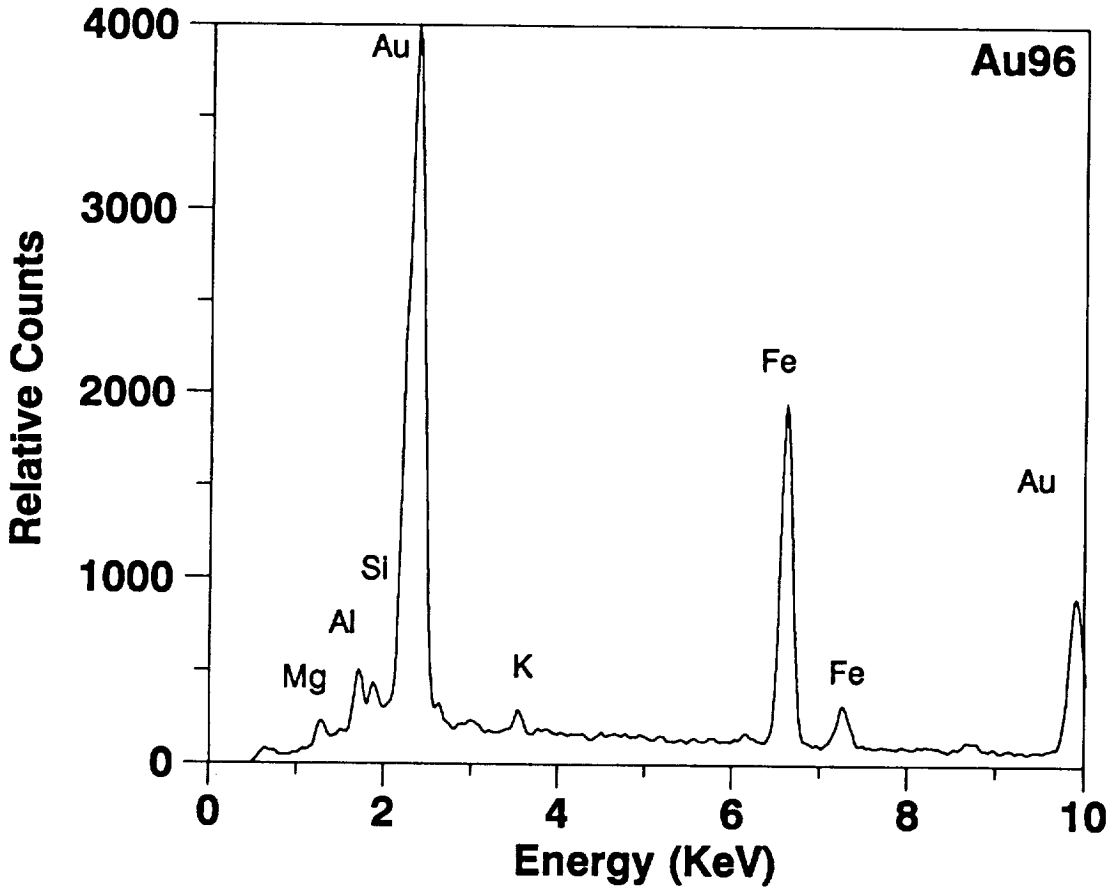


COMPONENT: EOOE
FEATURE: 96
CORE: LD-31

DIAMETER: 70 μm
ORIGIN: Natural



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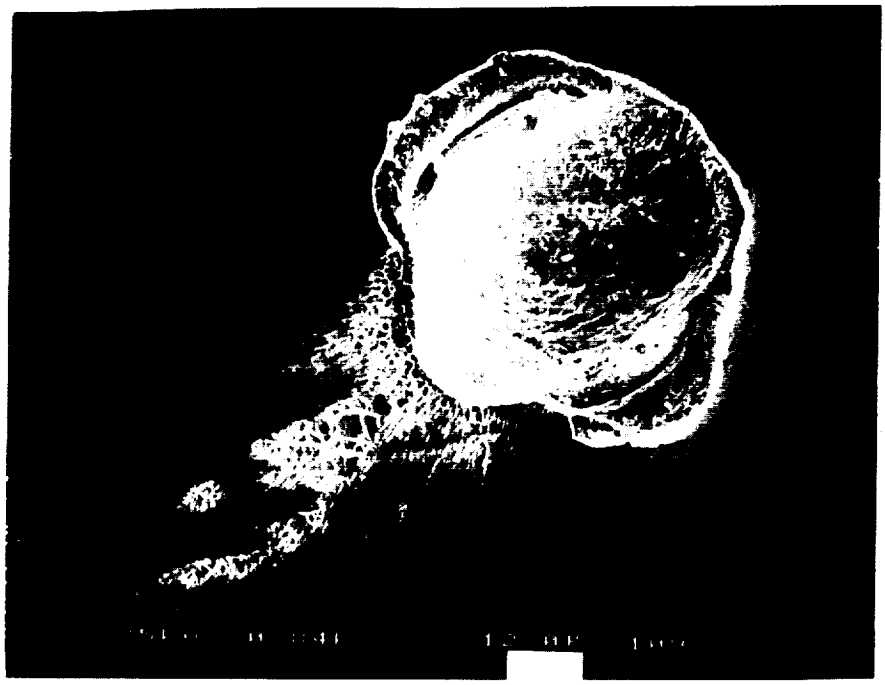
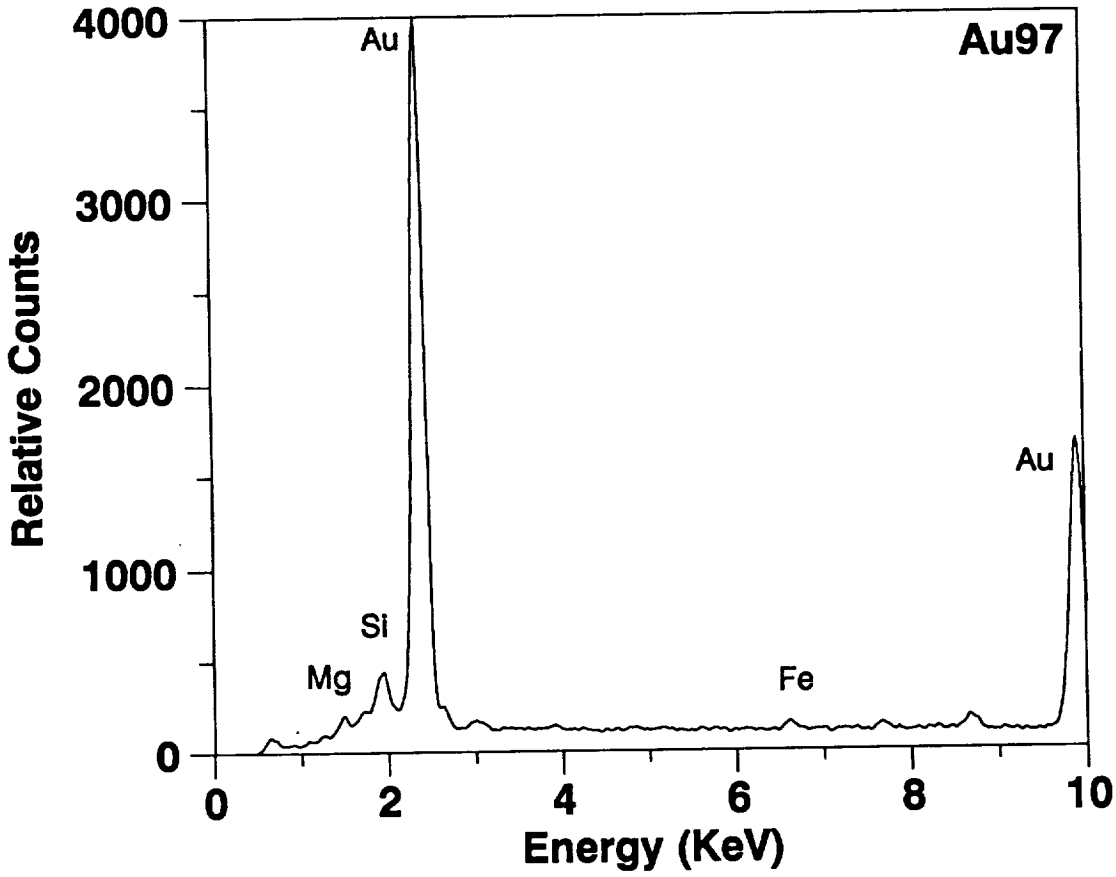


COMPONENT: EOOE
FEATURE: 97
CORE: LD-32

DIAMETER: 50 μm
ORIGIN: Natural



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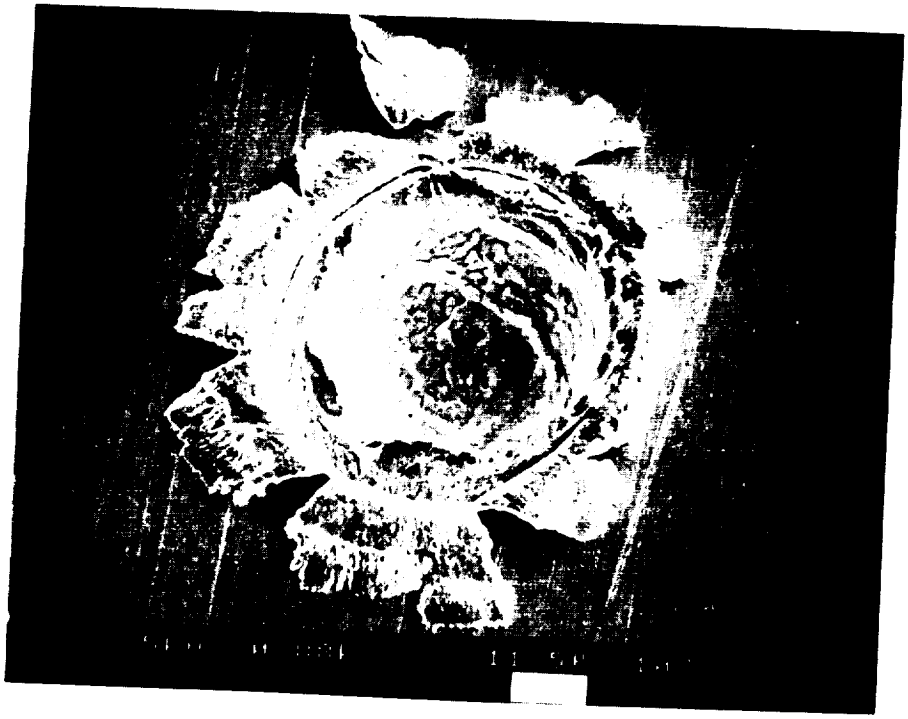
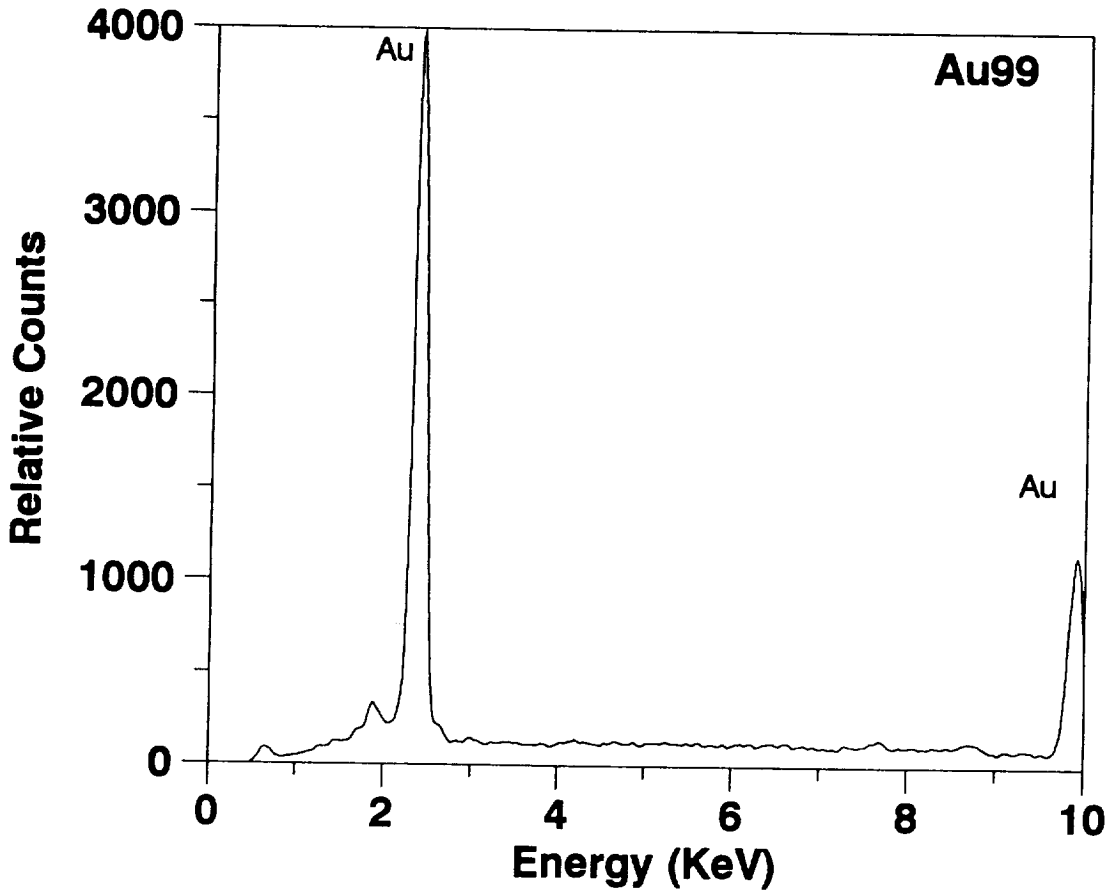


COMPONENT: EOOE
FEATURE: 99
CORE: LD-26

DIAMETER: 50 μm
ORIGIN: Unknown



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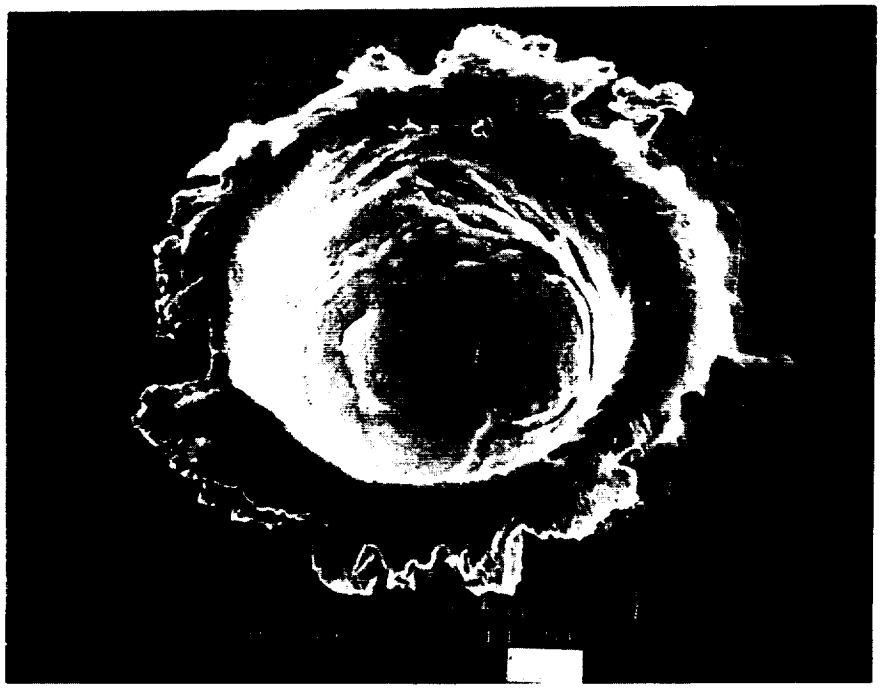
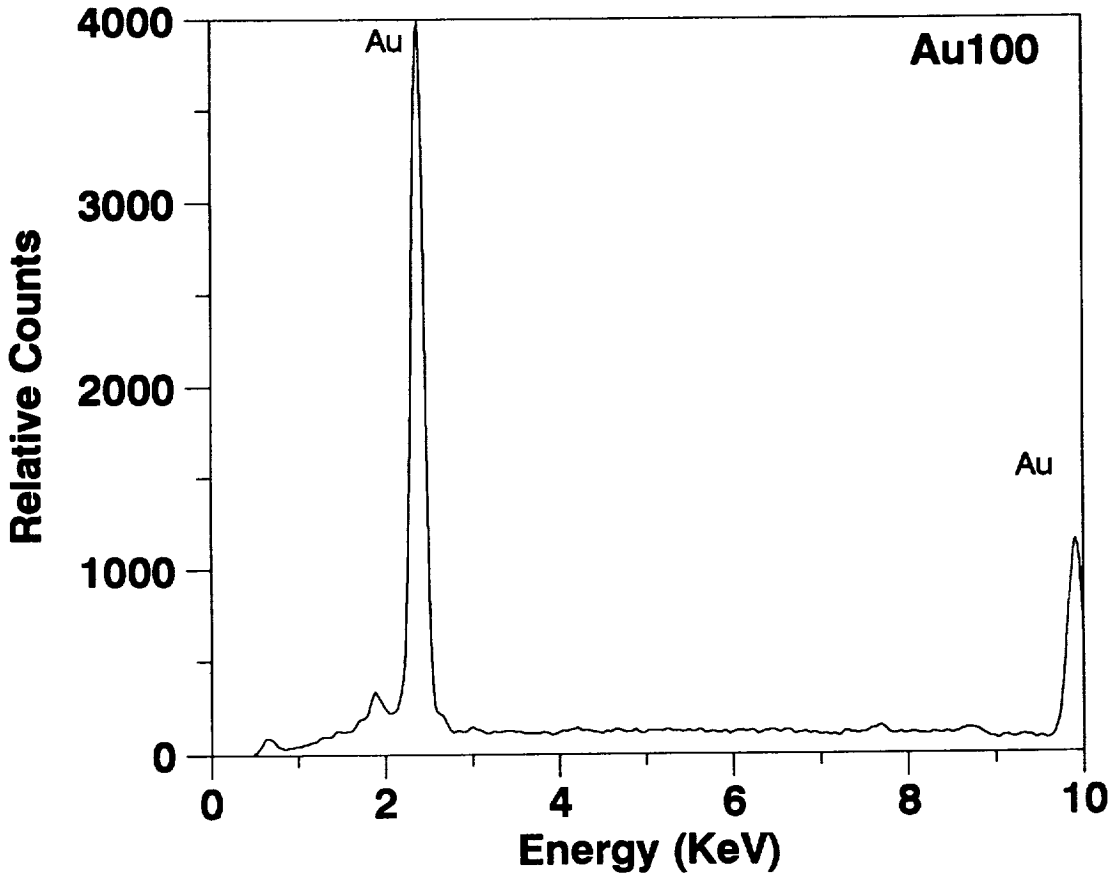


COMPONENT: EOOE
FEATURE: 100
CORE: LD-30

DIAMETER: 50 μm
ORIGIN: Unknown



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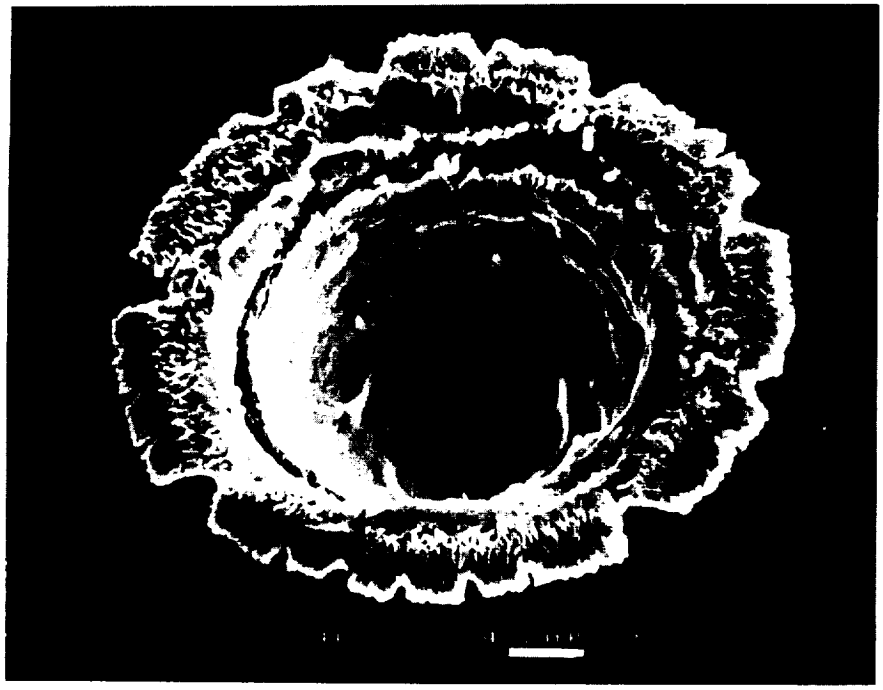
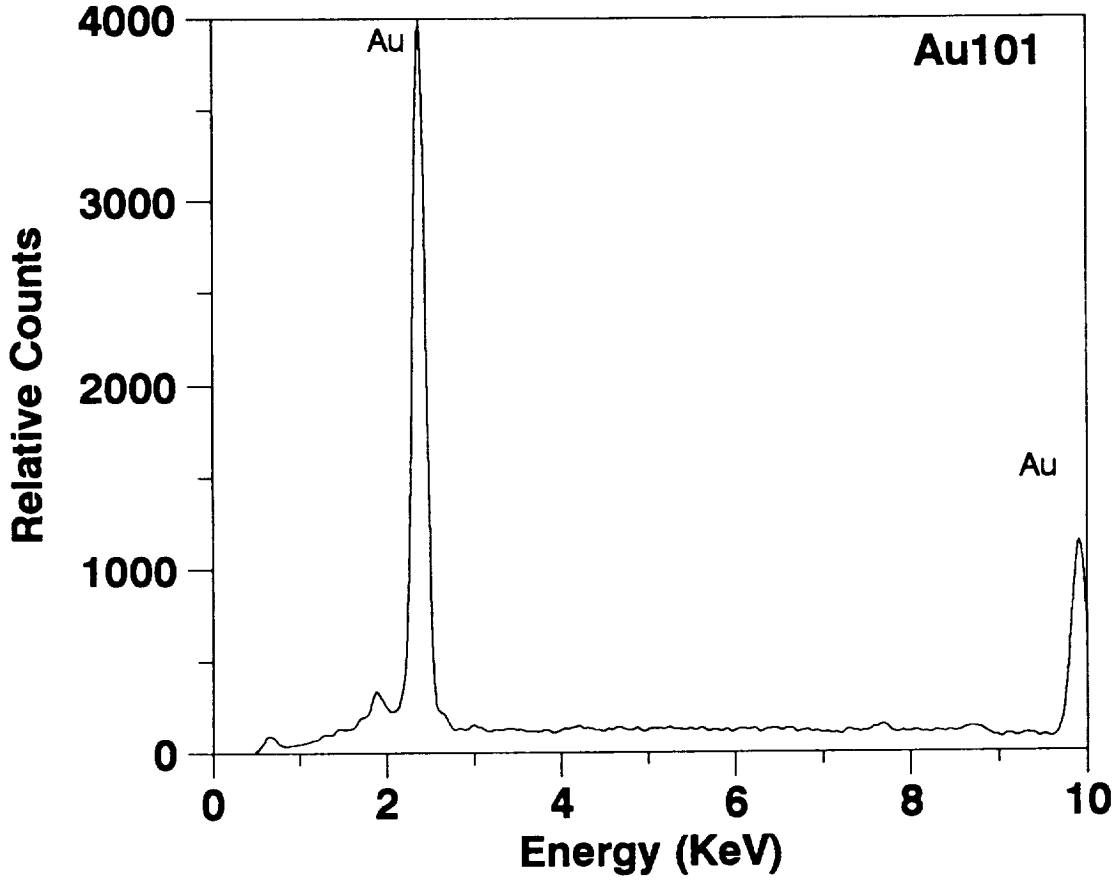


COMPONENT: EOOE
FEATURE: 101
CORE: LD-33

DIAMETER: 20 μm
ORIGIN: Unknown



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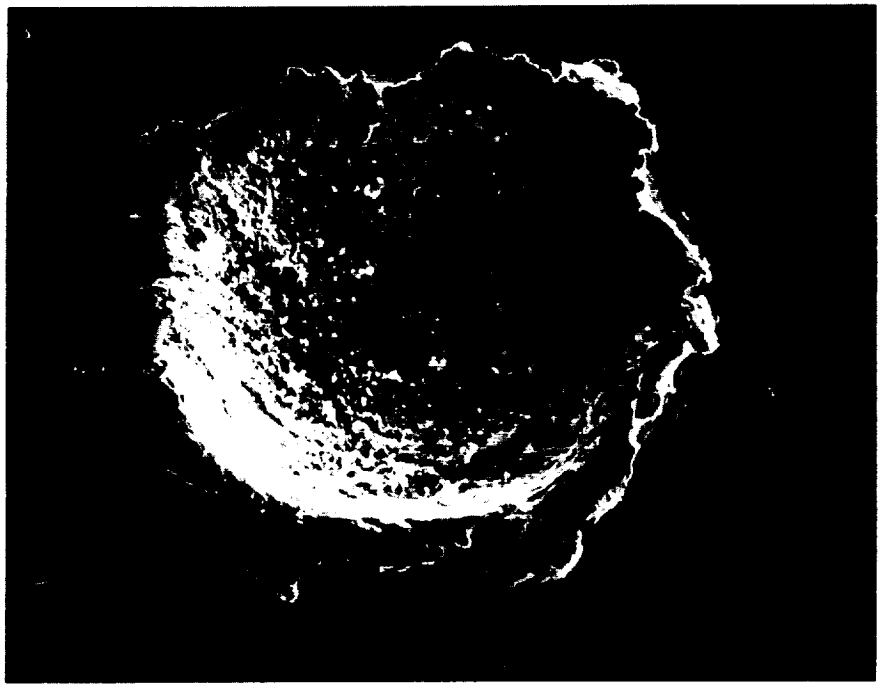
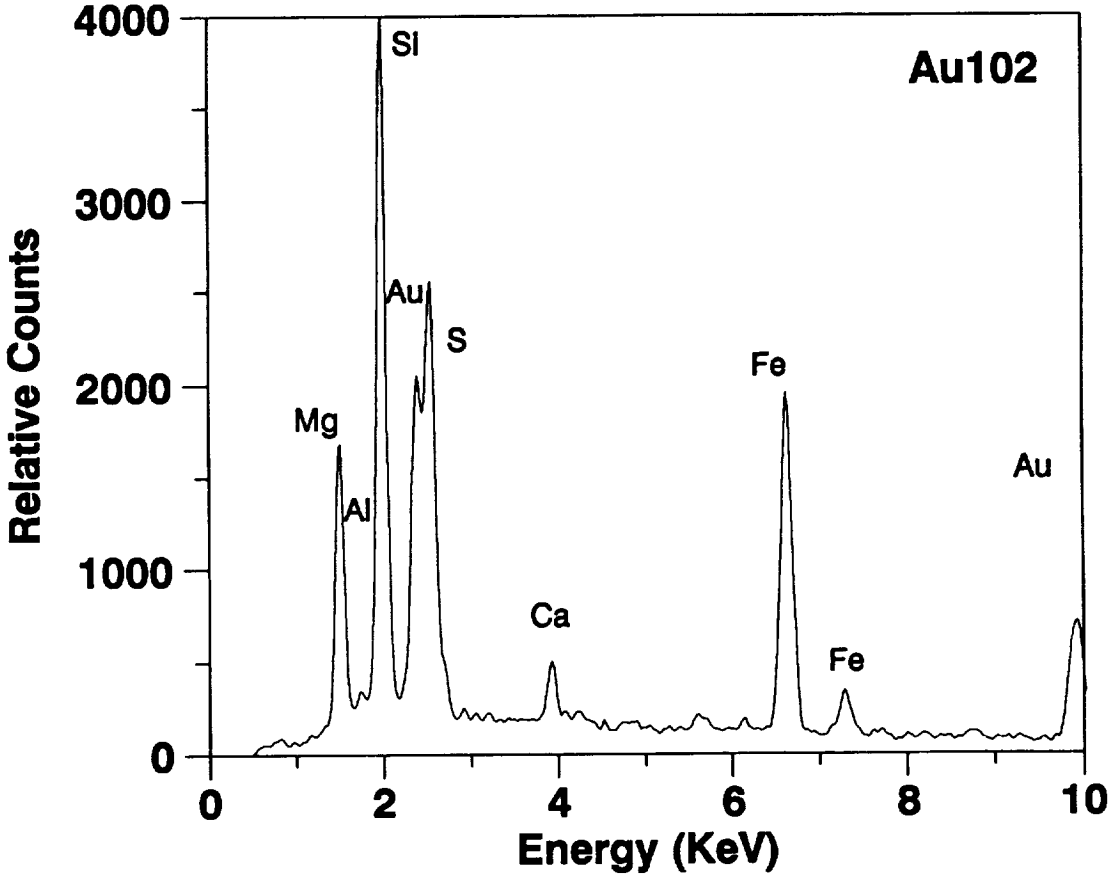


COMPONENT: EOOE
FEATURE: 102
CORE: LD-22

DIAMETER: 240 μm
ORIGIN: Natural
CLASS: Chondritic



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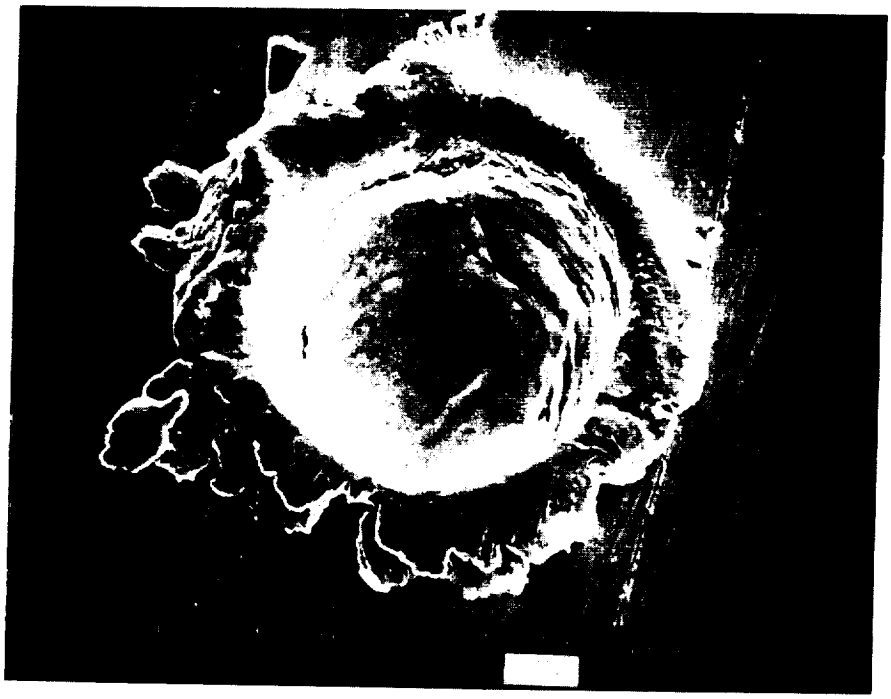
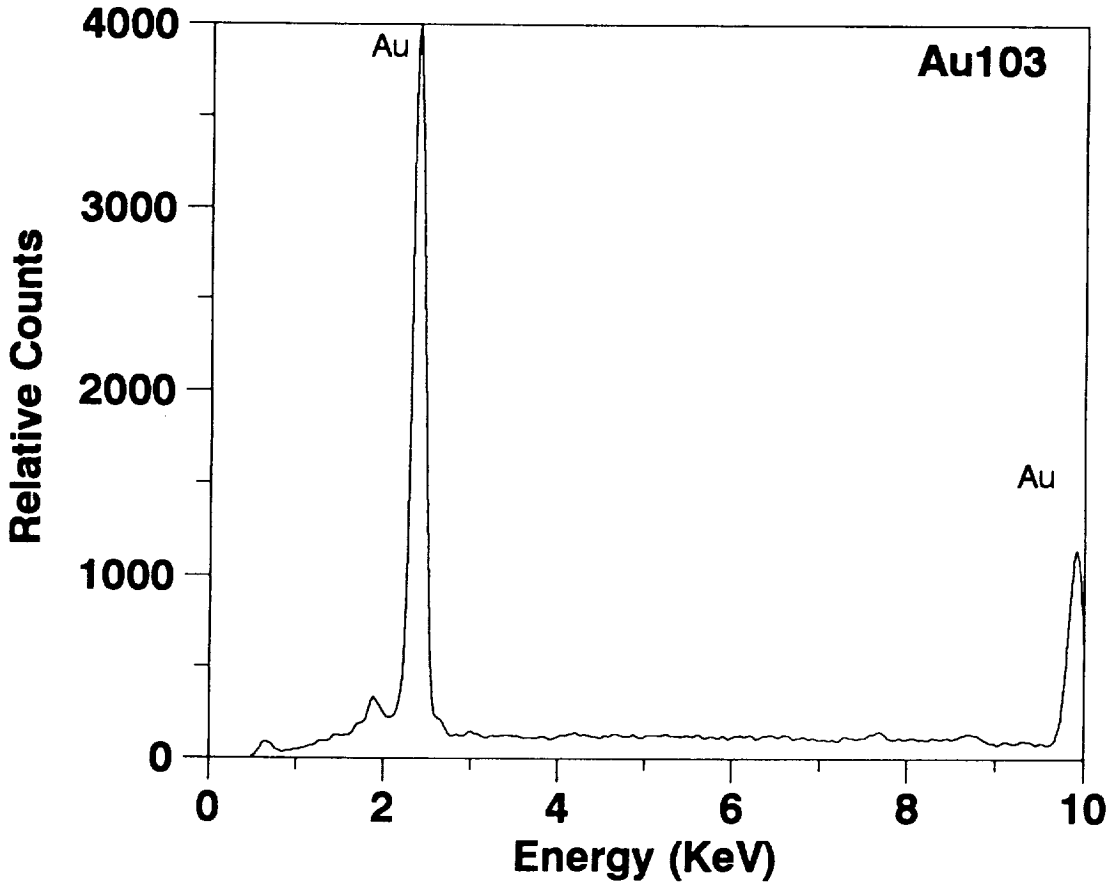


COMPONENT: EOOE
FEATURE: 103
CORE: LD-27

DIAMETER: 70 μm
ORIGIN: Unknown



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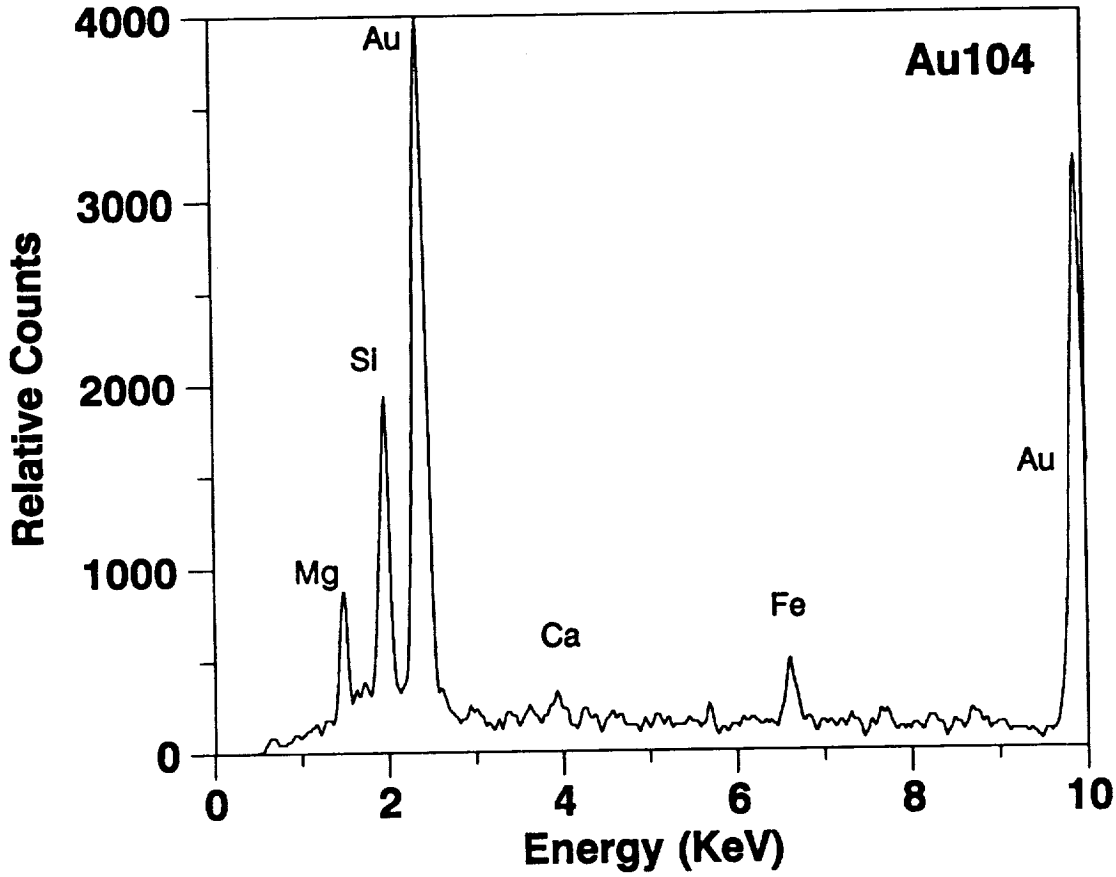
COMPONENT: EOOE
FEATURE: 104
CORE: LD-15

DIAMETER: 440 μm
ORIGIN: Natural



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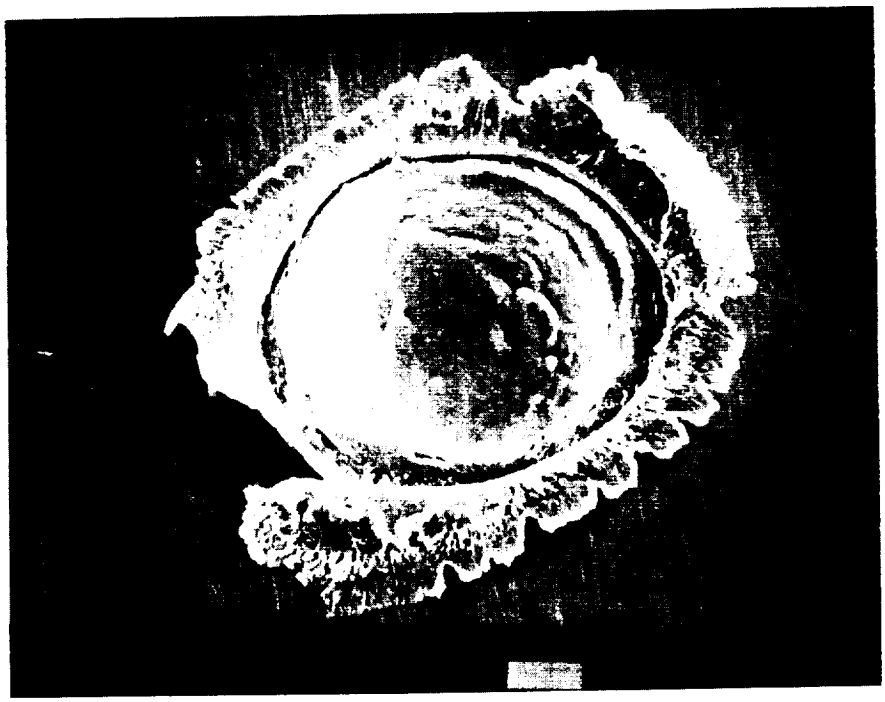
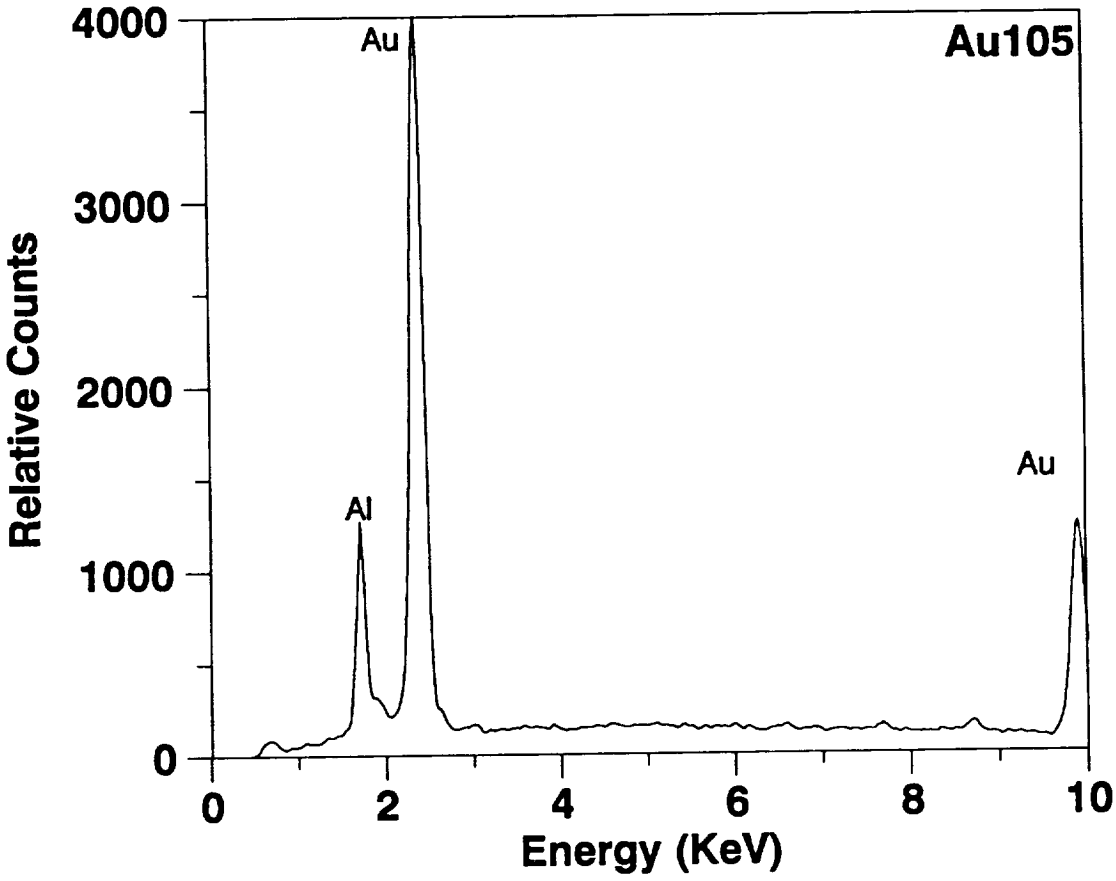


COMPONENT: EOOE
FEATURE: 105
CORE: LD-18

DIAMETER: 30 μm
ORIGIN: Man-made



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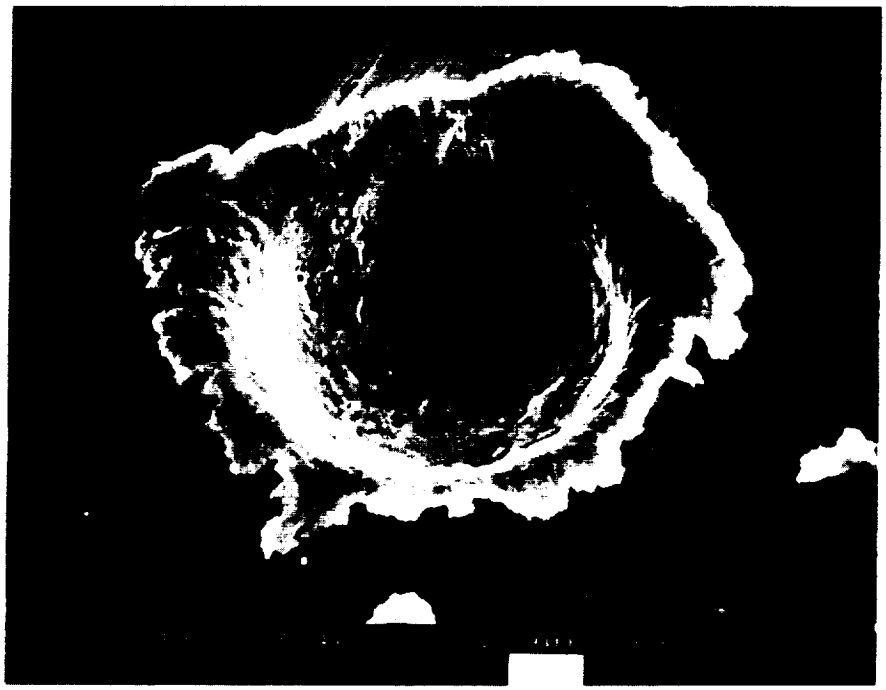
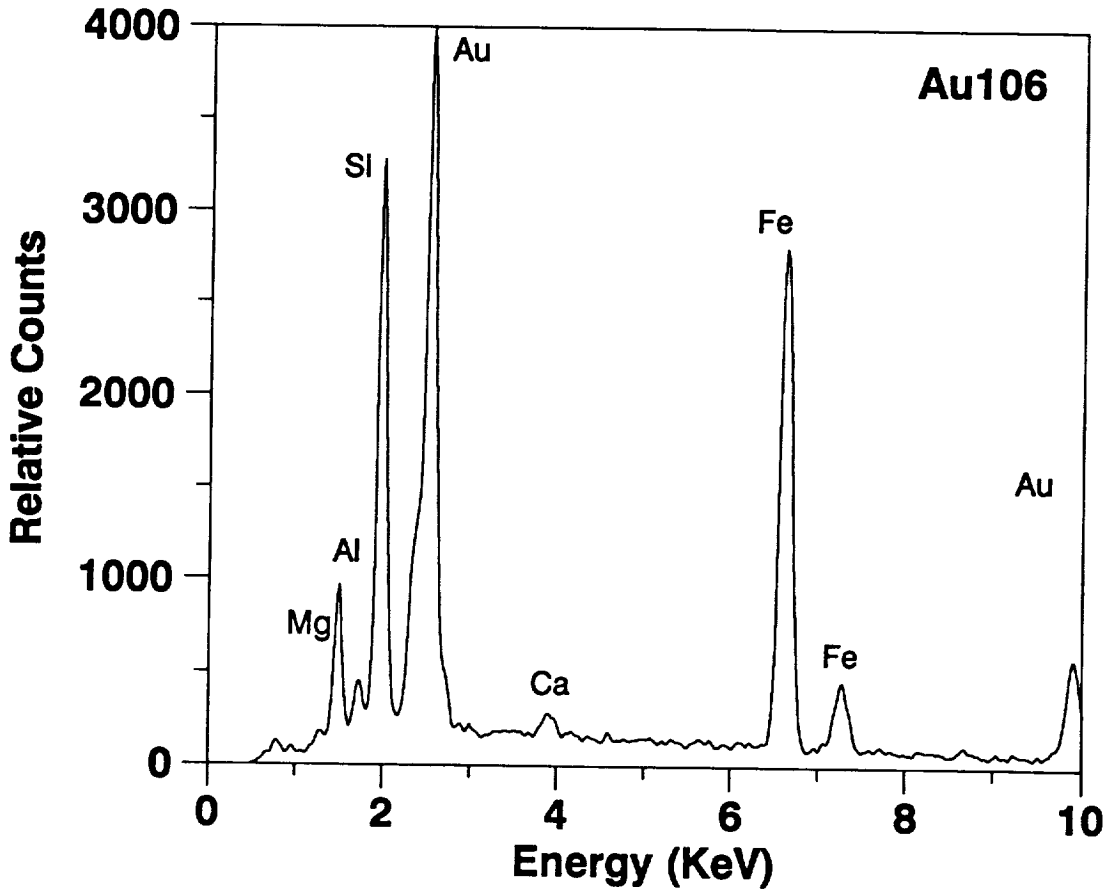


COMPONENT: EOOE
FEATURE: 106
CORE: LD-28

DIAMETER: 10 μm
ORIGIN: Natural
CLASS: Chondritic



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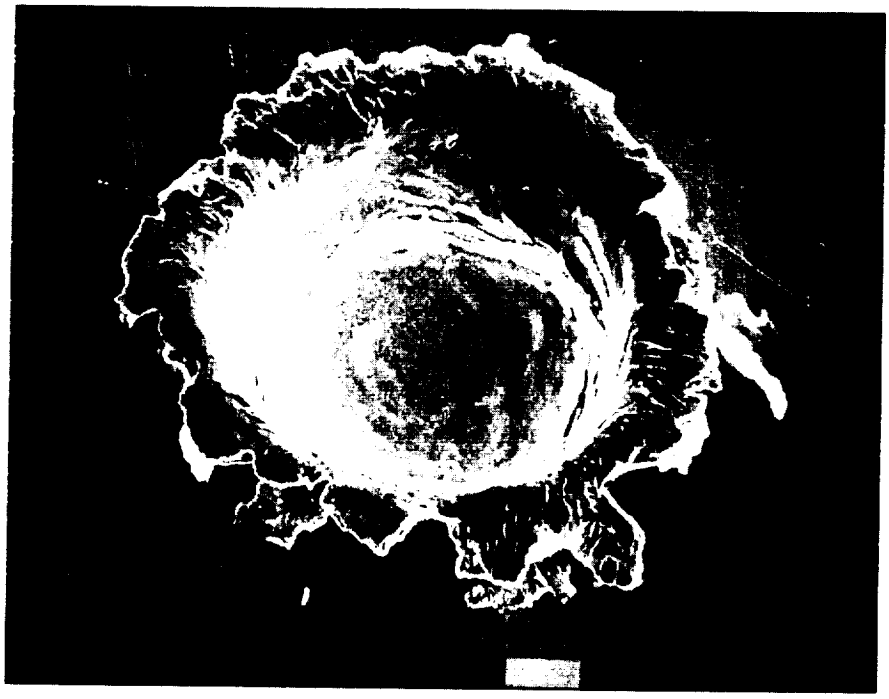
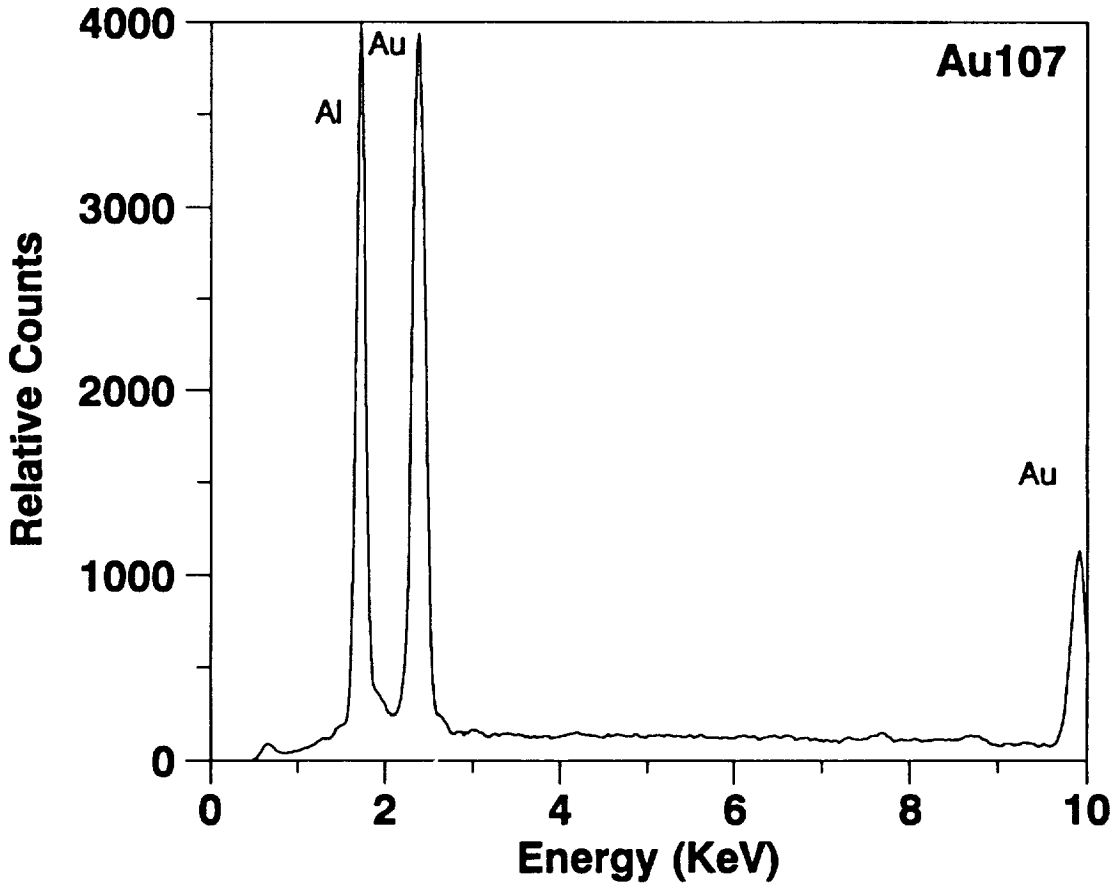


COMPONENT: EOOE
FEATURE: 107
CORE: LD-14

DIAMETER: 105 μm
ORIGIN: Man-made
CLASS: Debris



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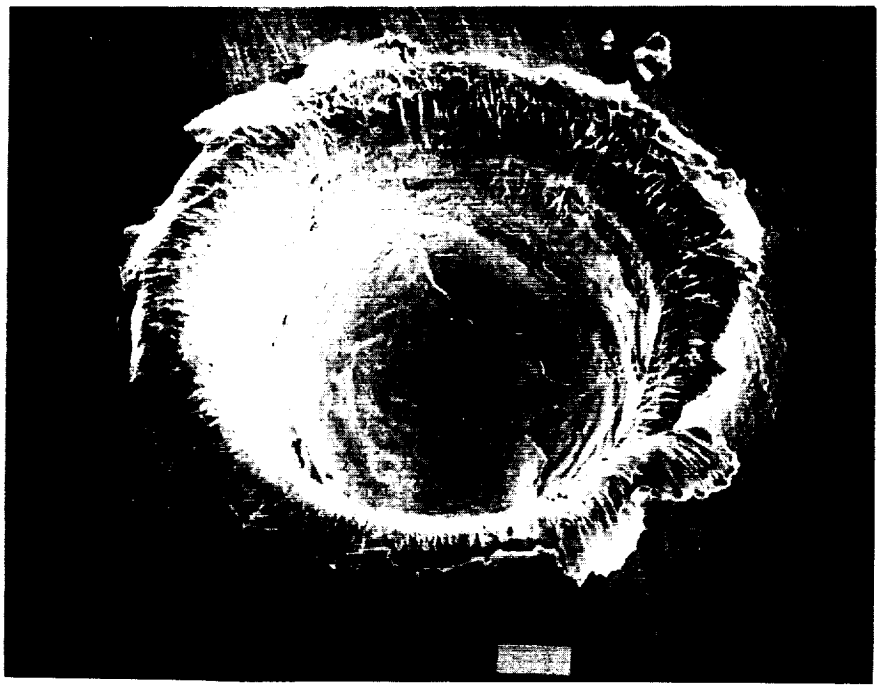
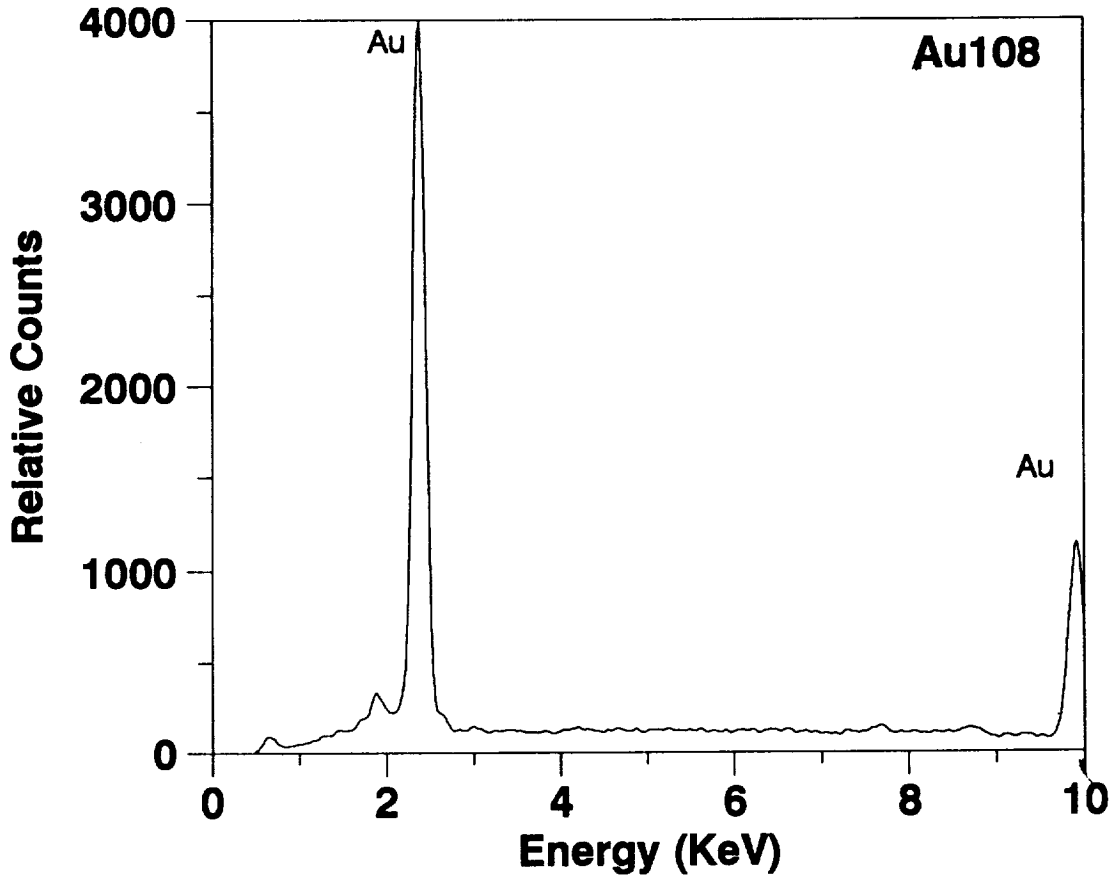


COMPONENT: EOOE
FEATURE: 108
CORE: LD-16

DIAMETER: 210 μm
ORIGIN: Unknown



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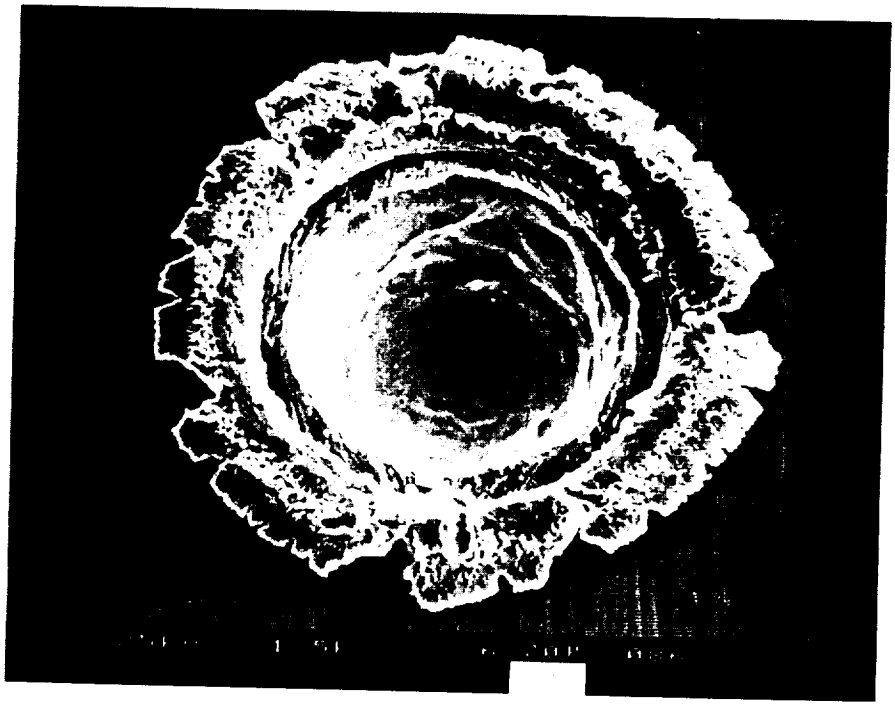
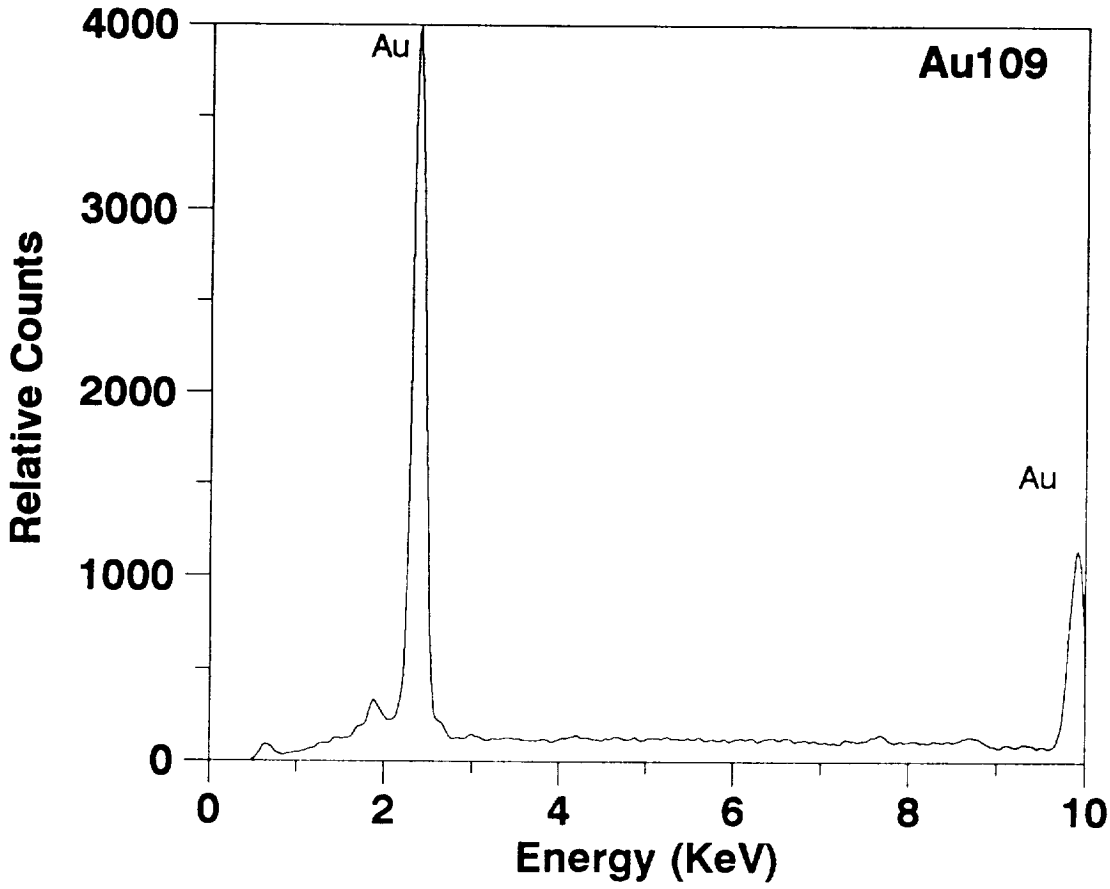


COMPONENT: EOOE
FEATURE: 109
CORE: LD-17

DIAMETER: 30 μm
ORIGIN: Unknown



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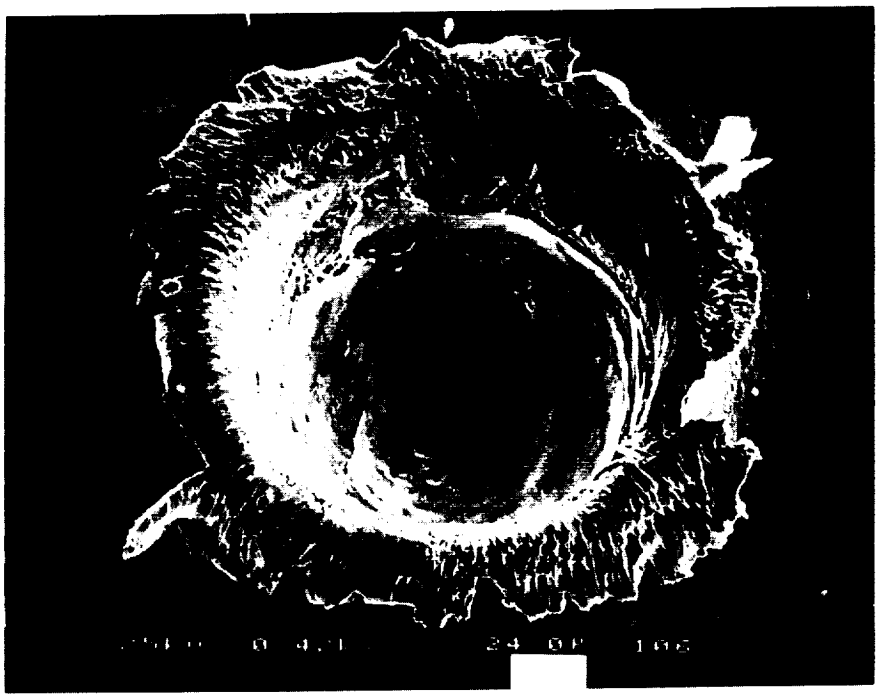
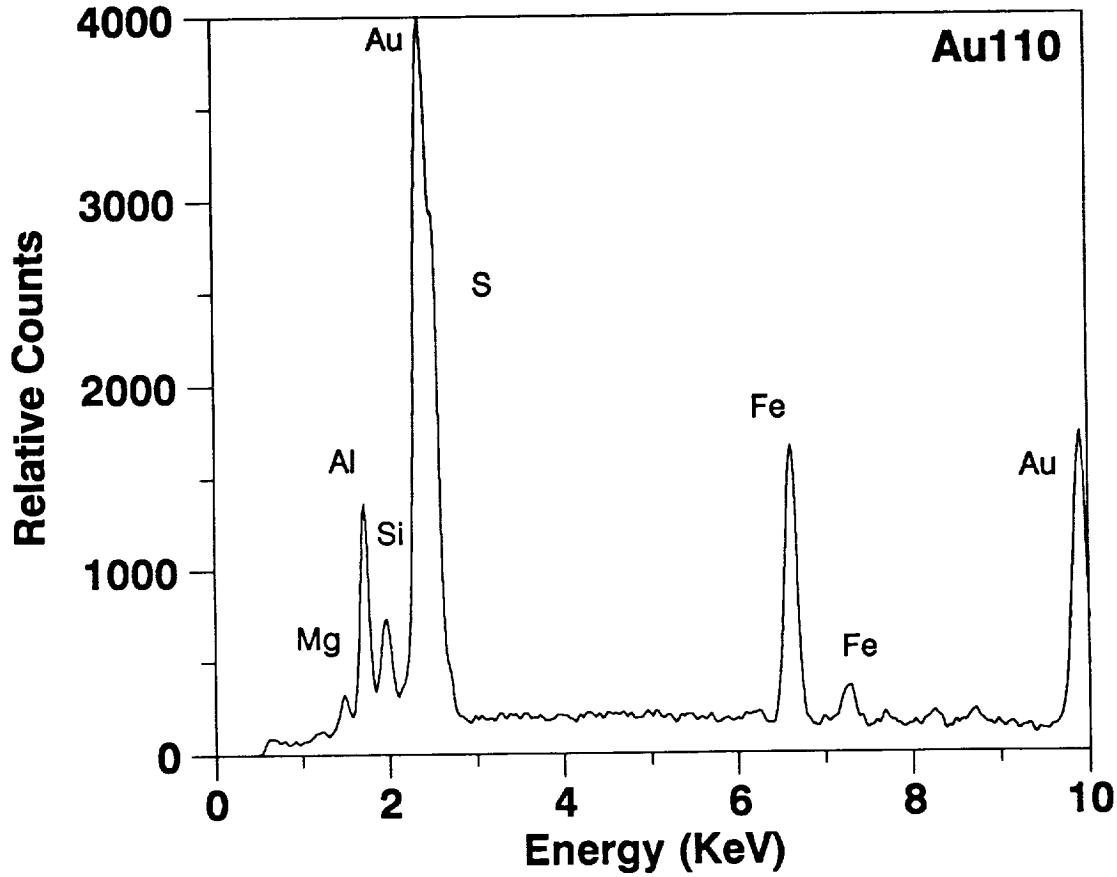


COMPONENT: EOOE
FEATURE: 110
CORE: LD-29

DIAMETER: 170 μm
ORIGIN: Natural
CLASS: Chondritic



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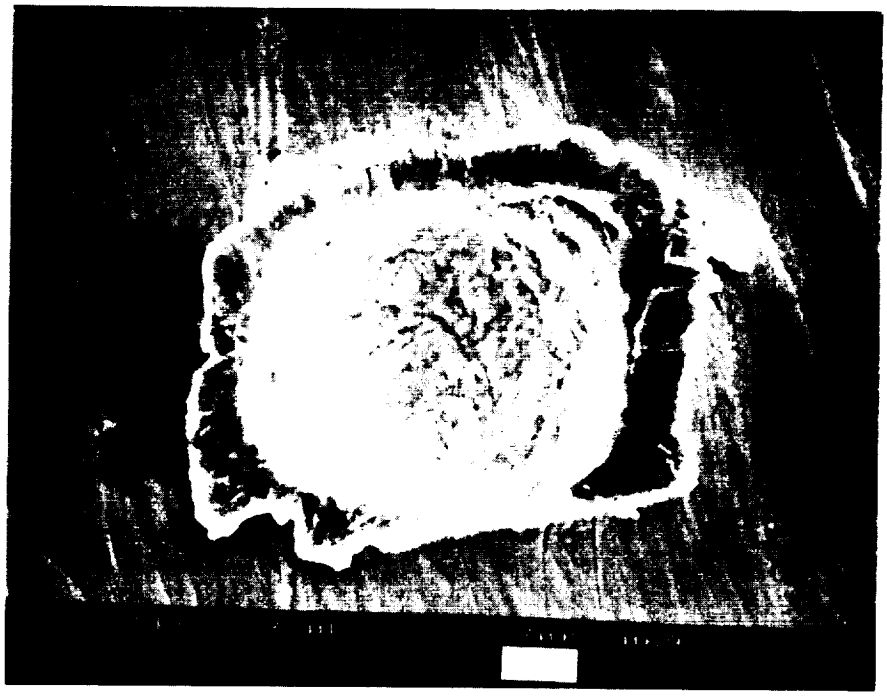
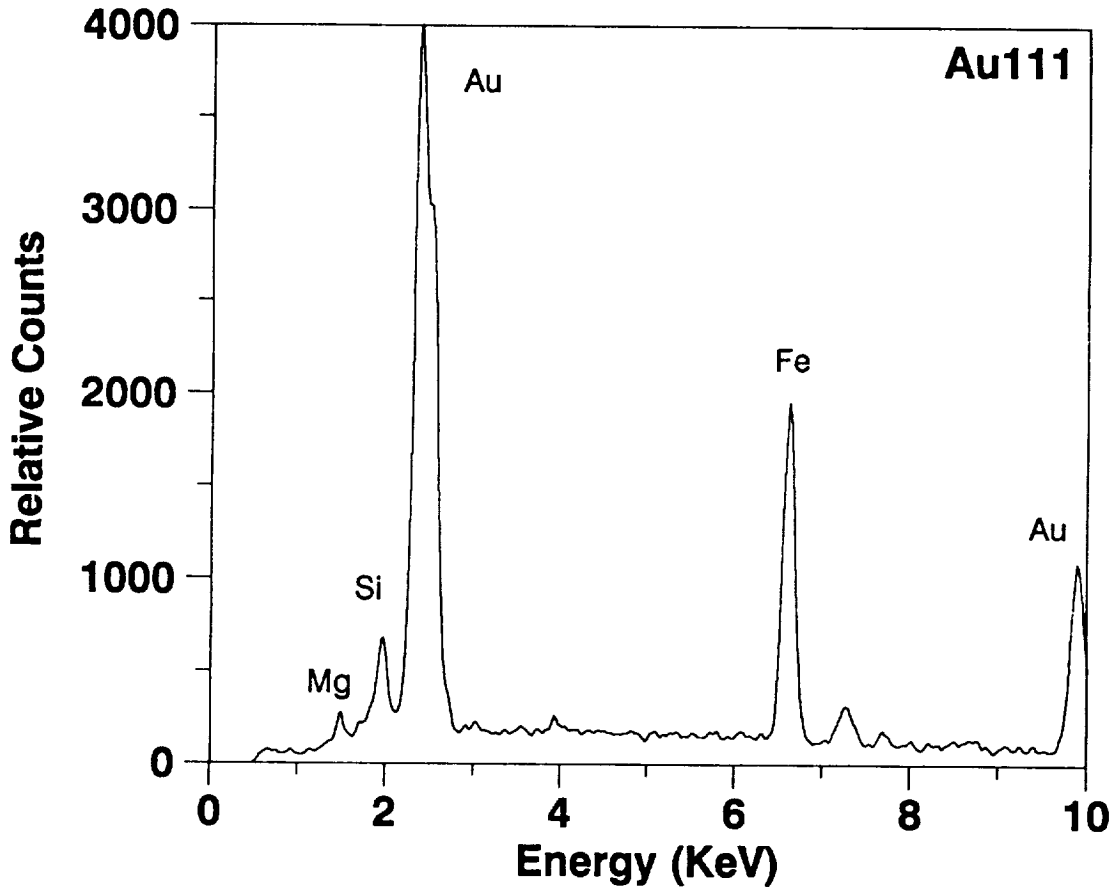


COMPONENT: EOOE
FEATURE: 111
CORE: LD-6

DIAMETER: 15 μm
ORIGIN: Natural



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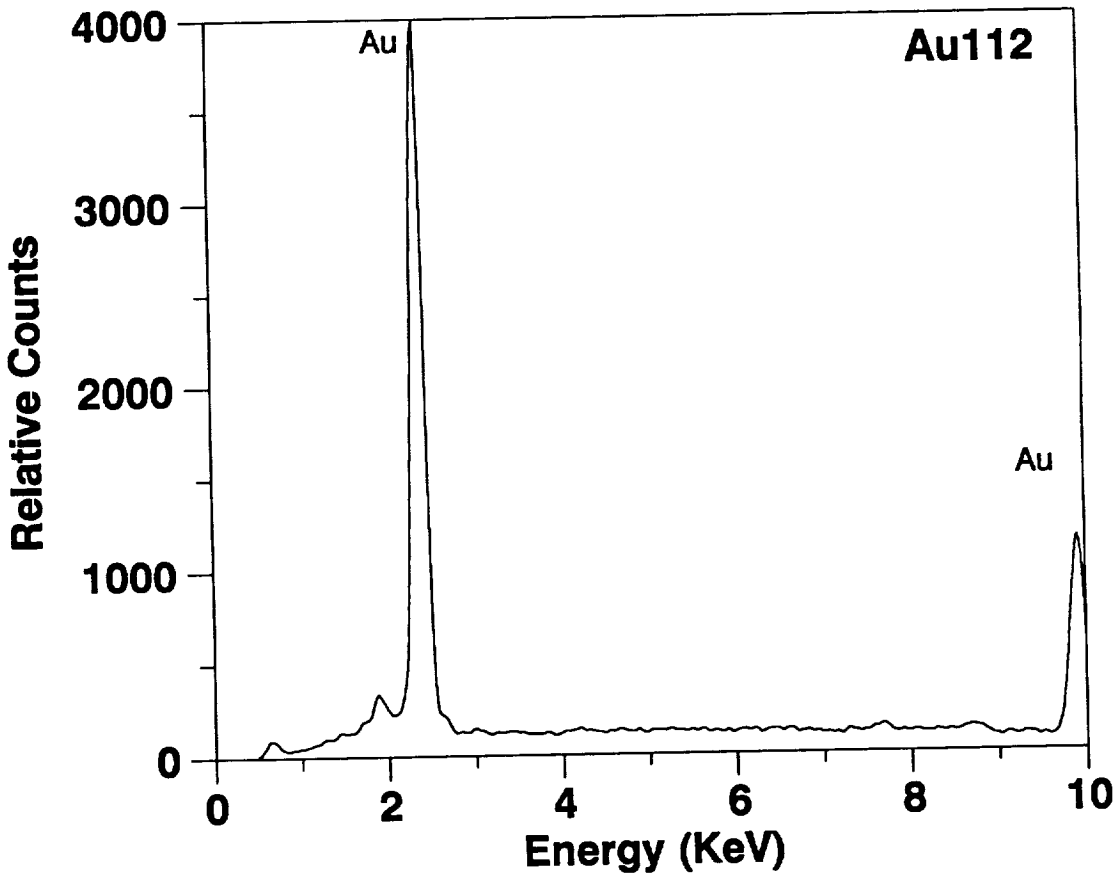
COMPONENT: EOOF
FEATURE: 112
CORE: LD-82

DIAMETER: 15 μm
ORIGIN: Unknown



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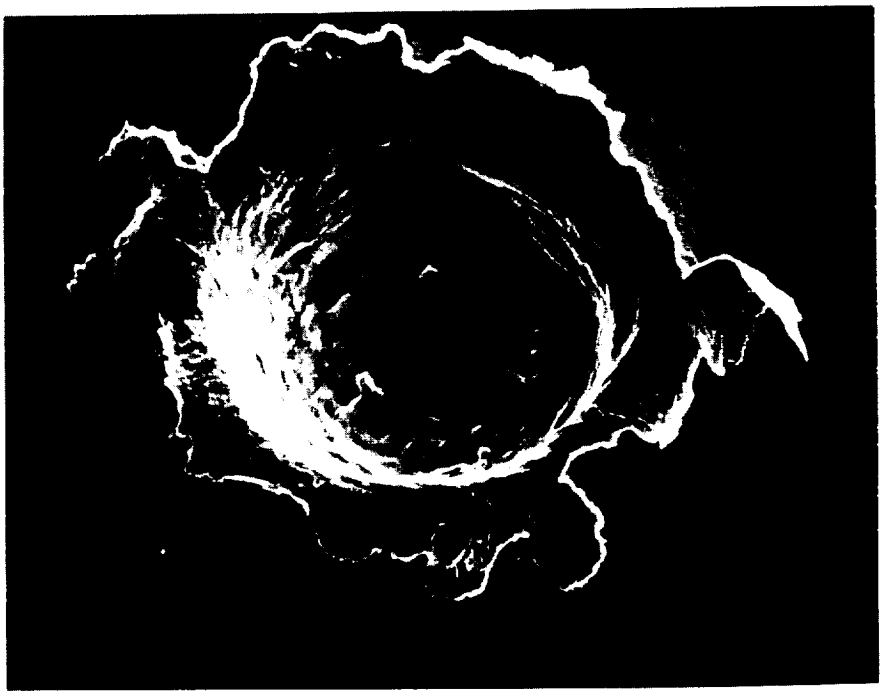
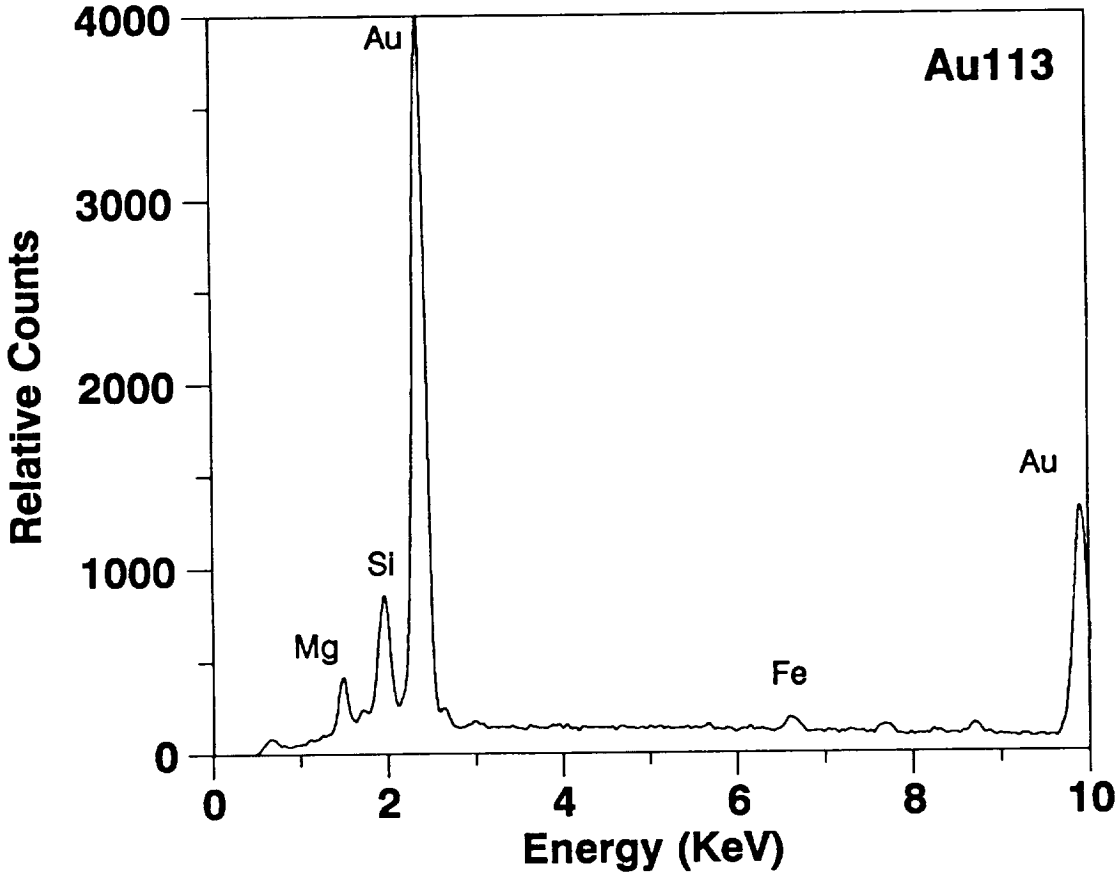


COMPONENT: EOOF
FEATURE: 113
CORE: LD-83

DIAMETER: 55 μm
ORIGIN: Natural
CLASS: Chondritic



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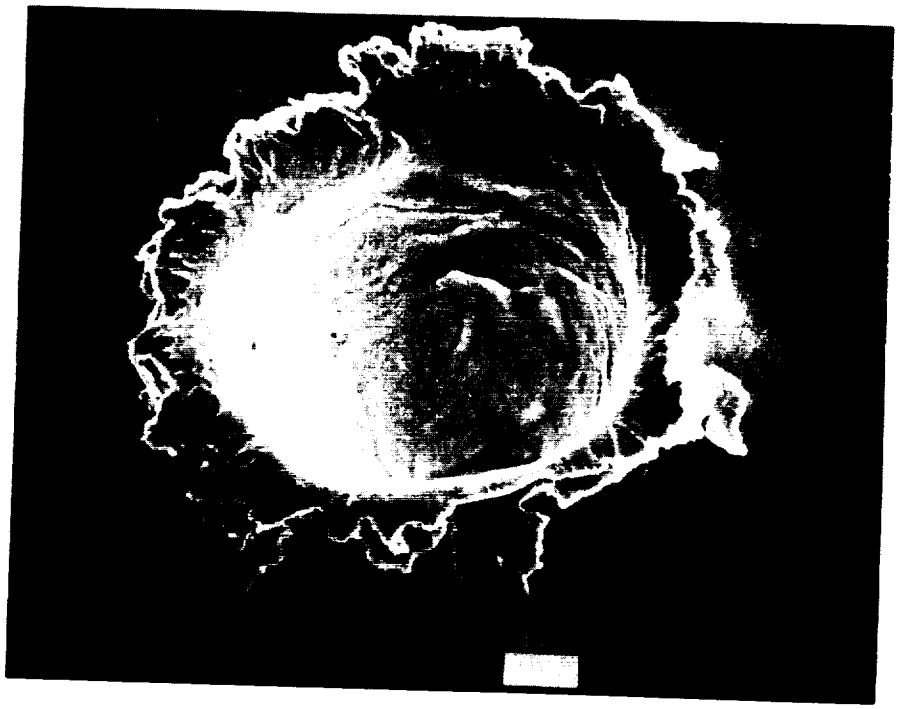
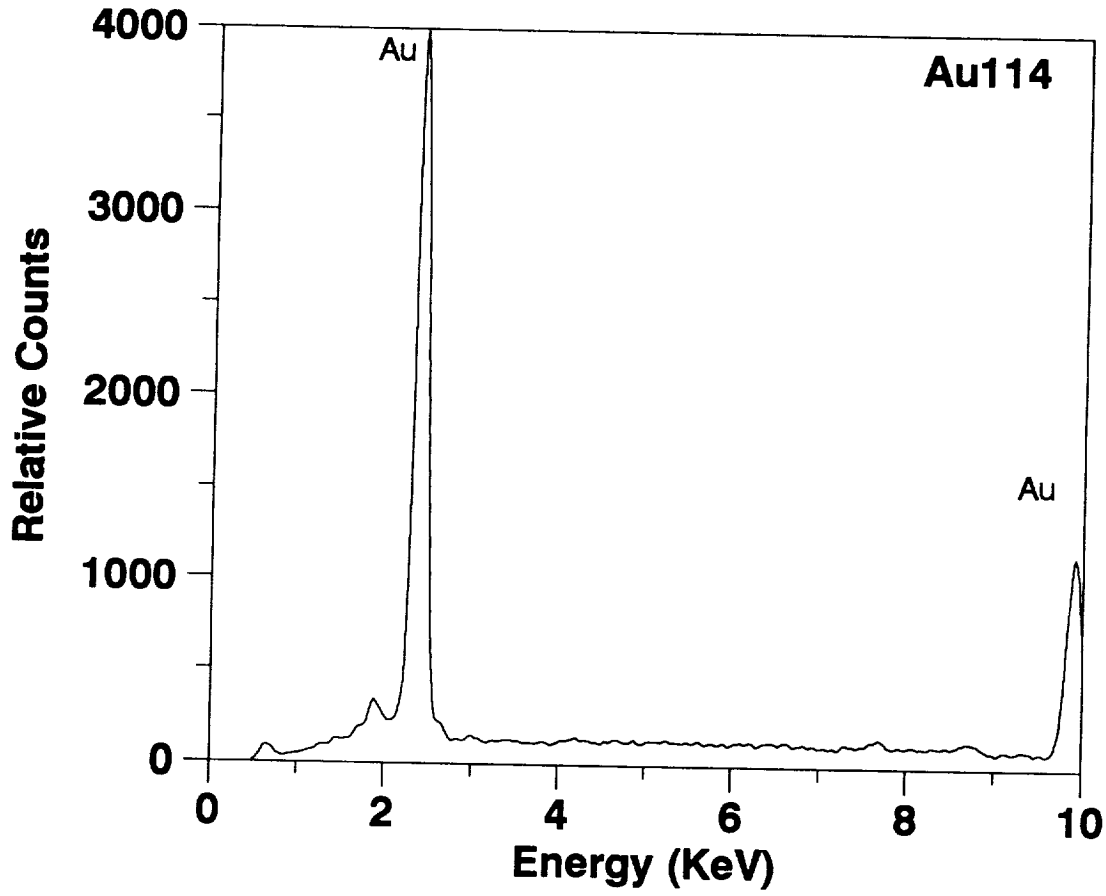


COMPONENT: EOOF
FEATURE: 114
CORE: LD-81

DIAMETER: 40 μm
ORIGIN: Unknown



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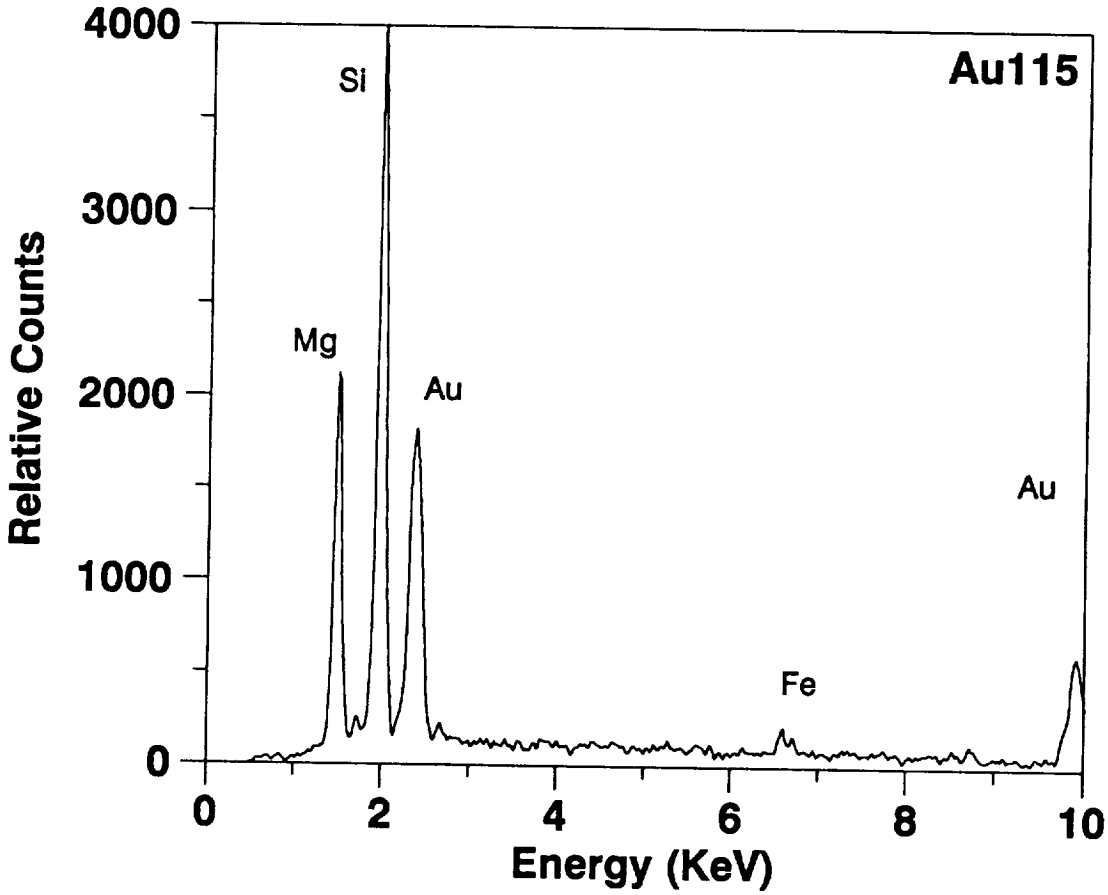
COMPONENT: EOOF
FEATURE: 115
CORE: LD-51

DIAMETER: 55 μm
ORIGIN: Natural
CLASS: Chondritic



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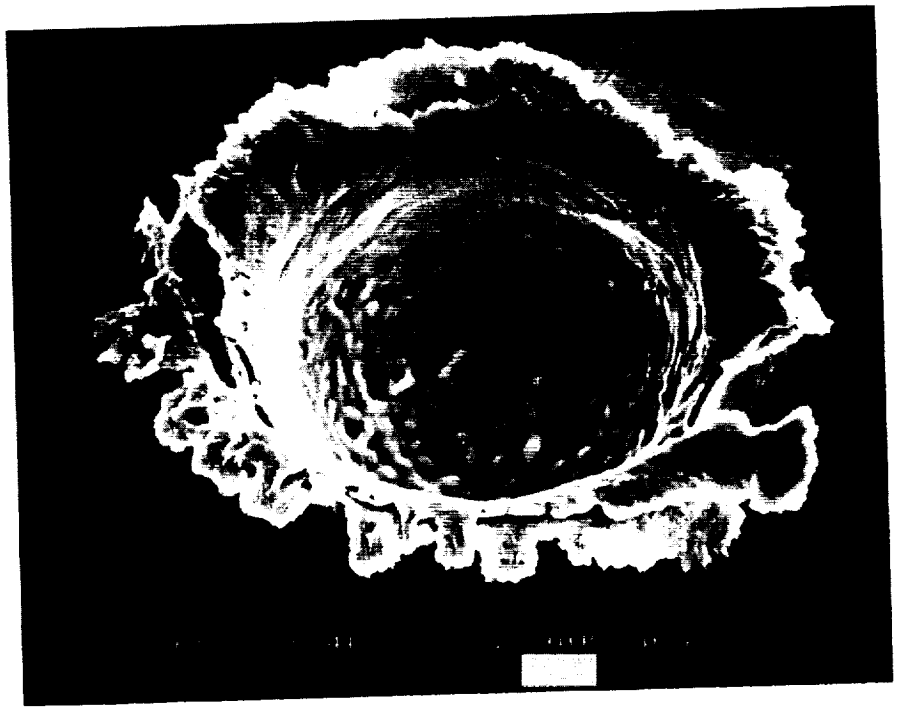
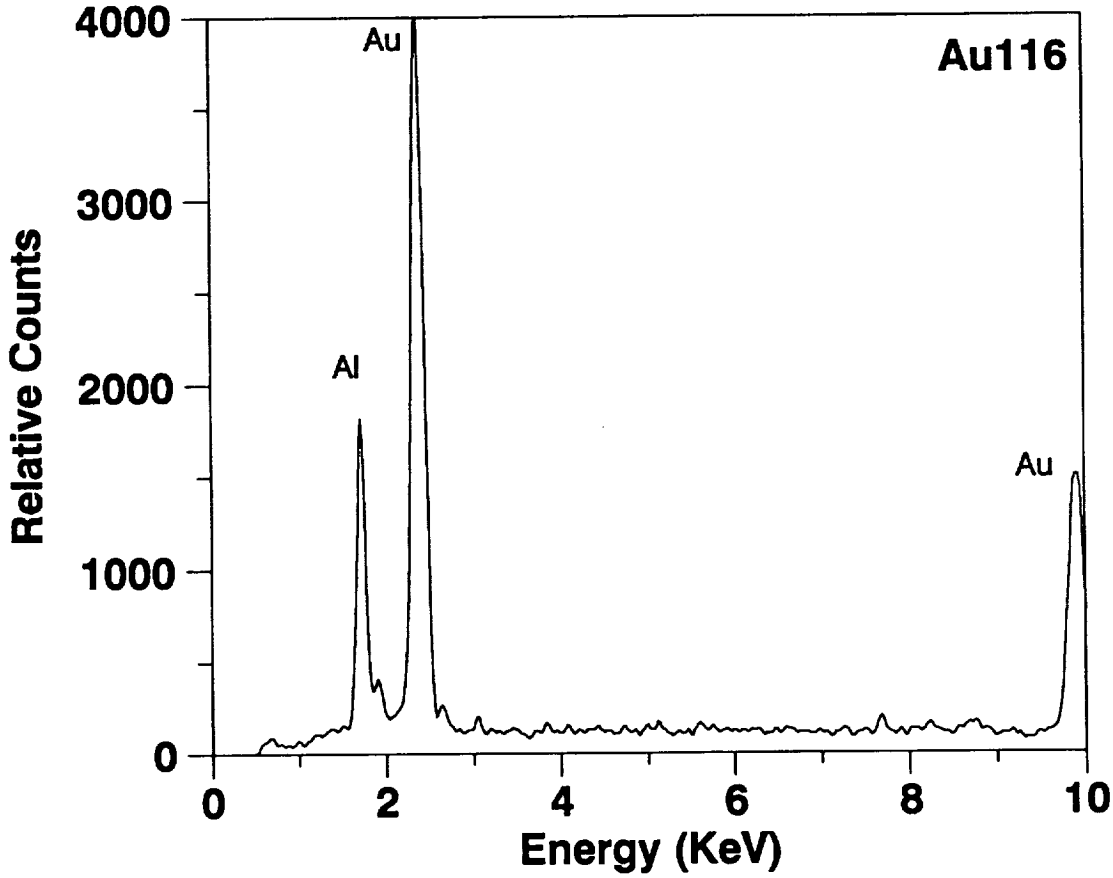


COMPONENT: EOOF
FEATURE: 116
CORE: LD-53

DIAMETER: 10 μm
ORIGIN: Man-made



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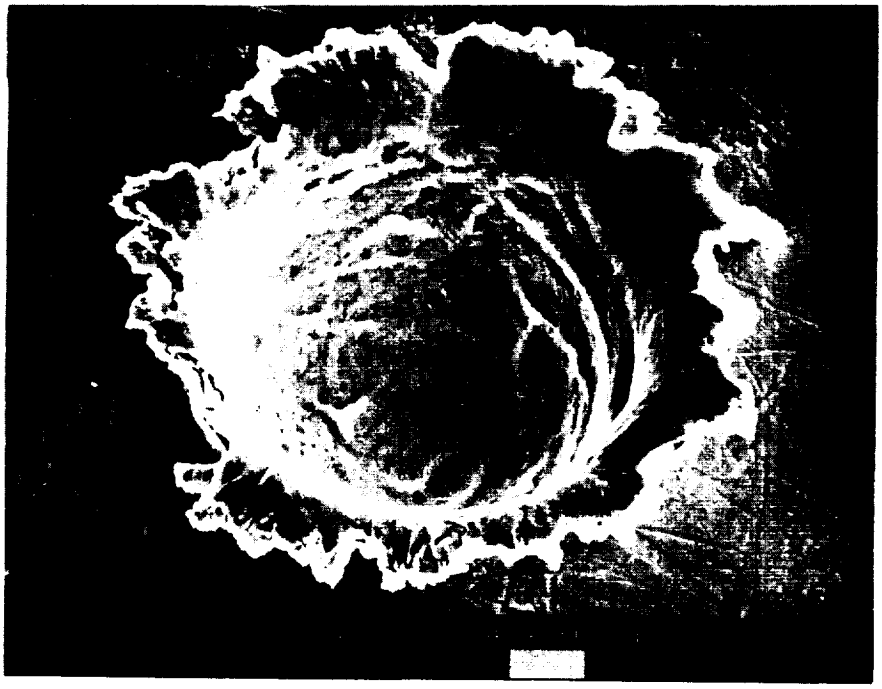
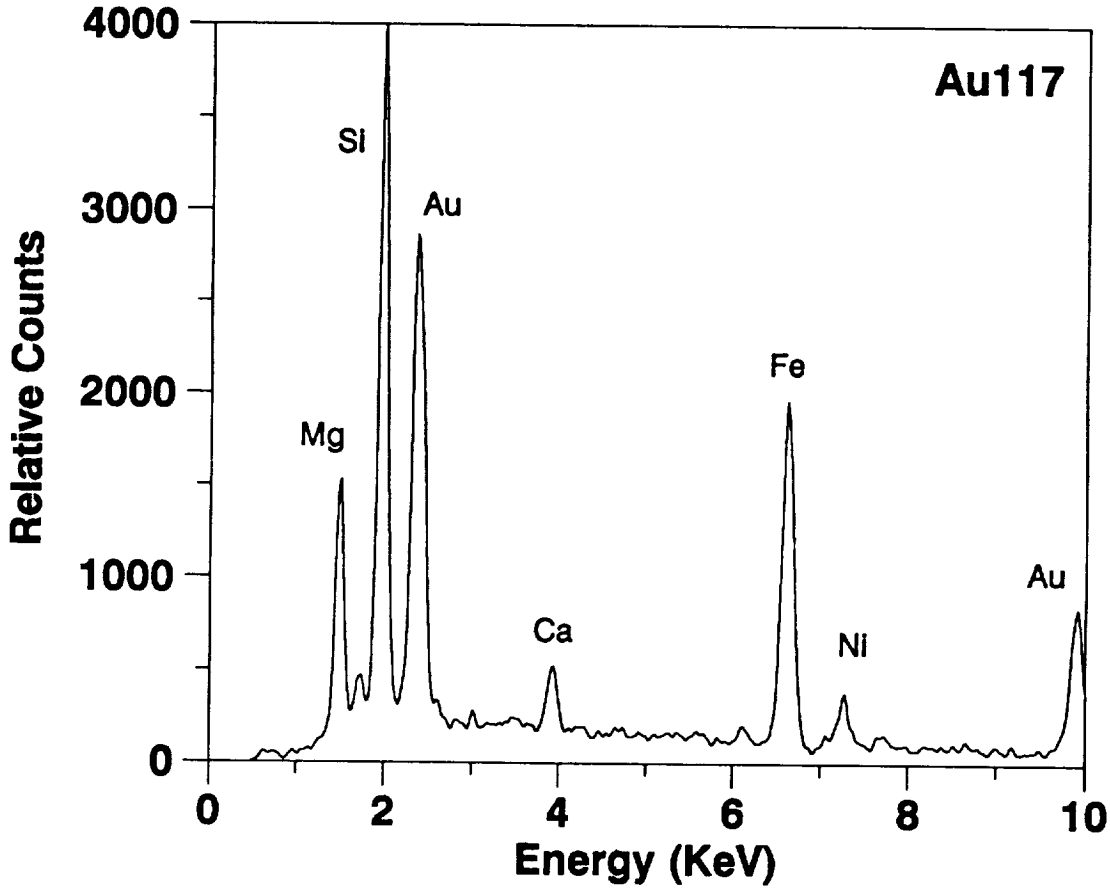


COMPONENT: EOOF
FEATURE: 117
CORE: LD-52

DIAMETER: 20 μm
ORIGIN: Natural



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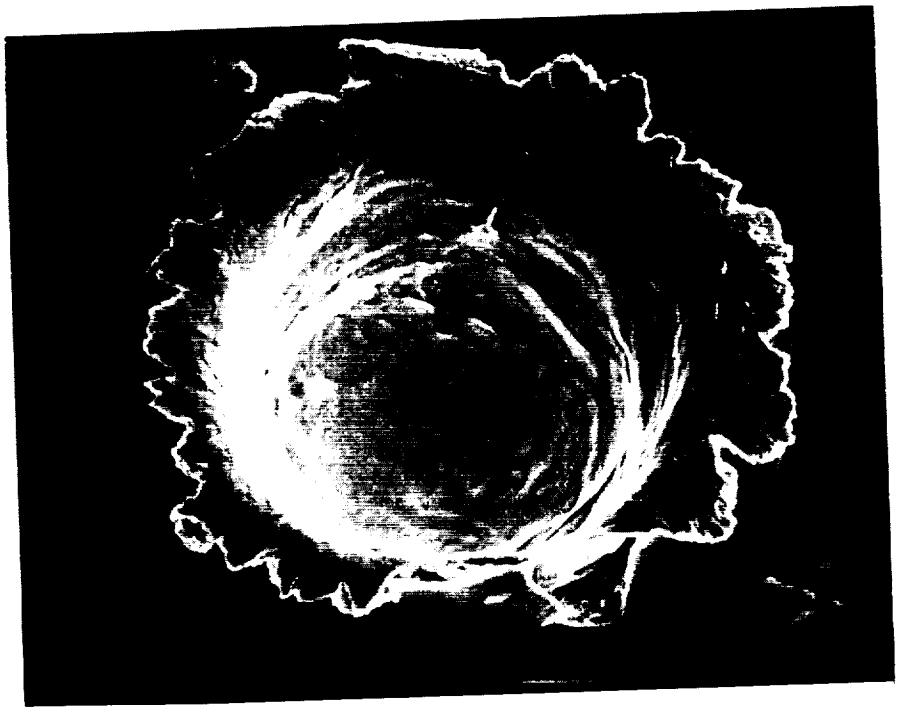
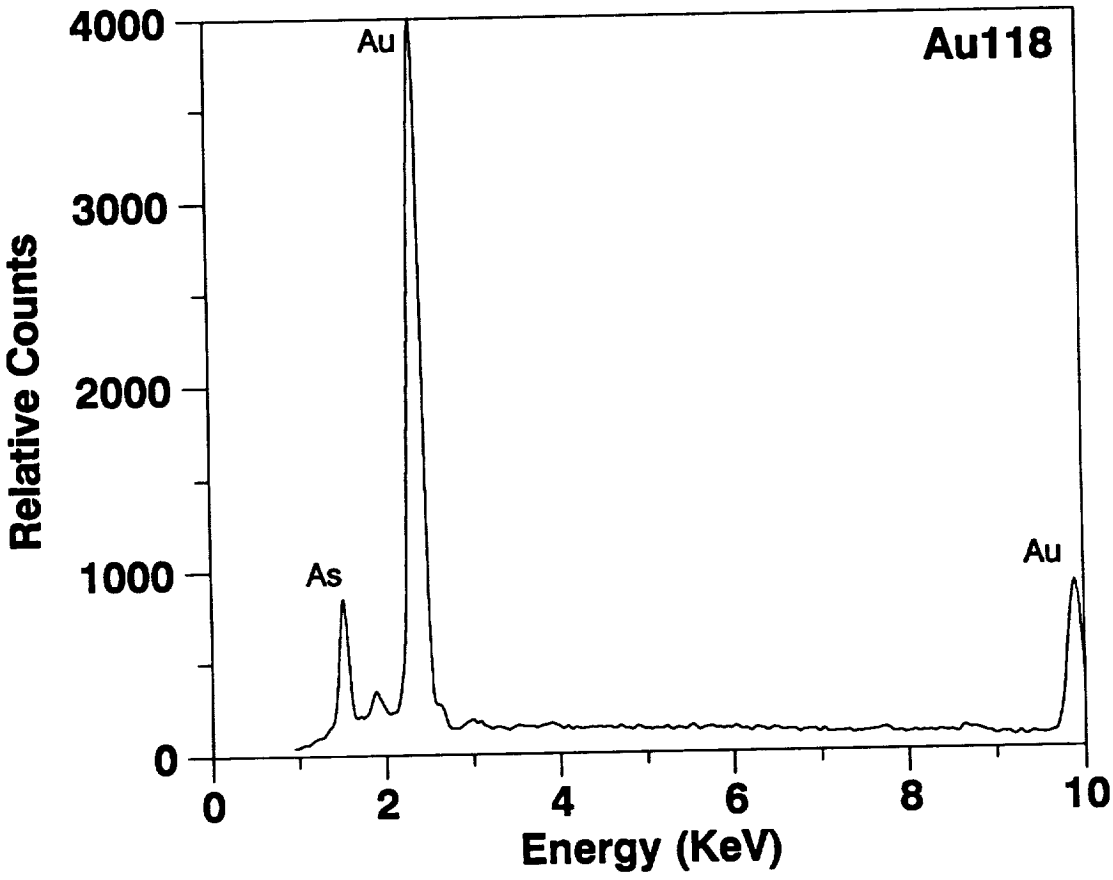


COMPONENT: EOOF
FEATURE: 118
CORE: LD-57

DIAMETER: 65 μm
ORIGIN: Unknown



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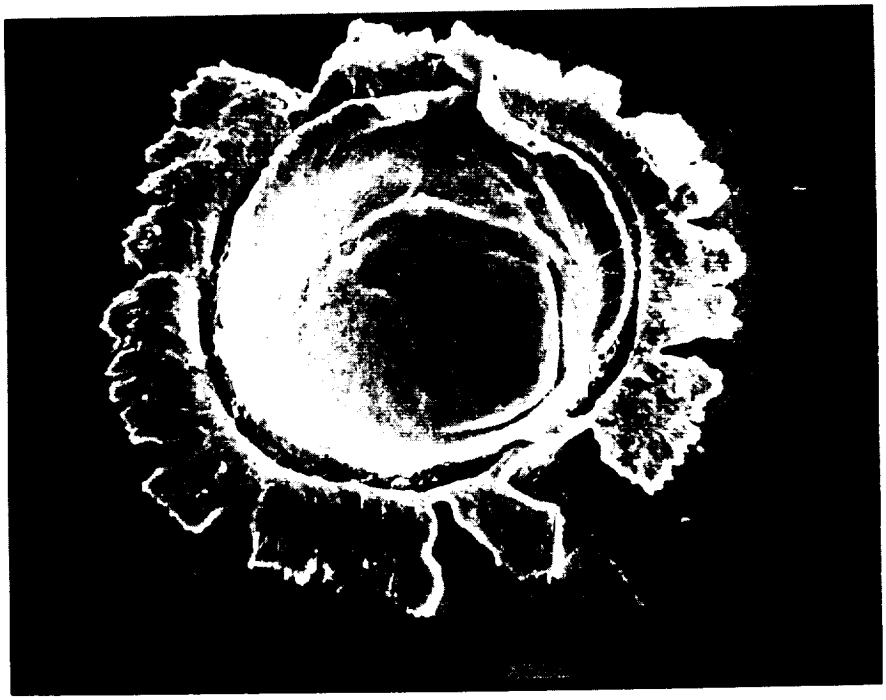
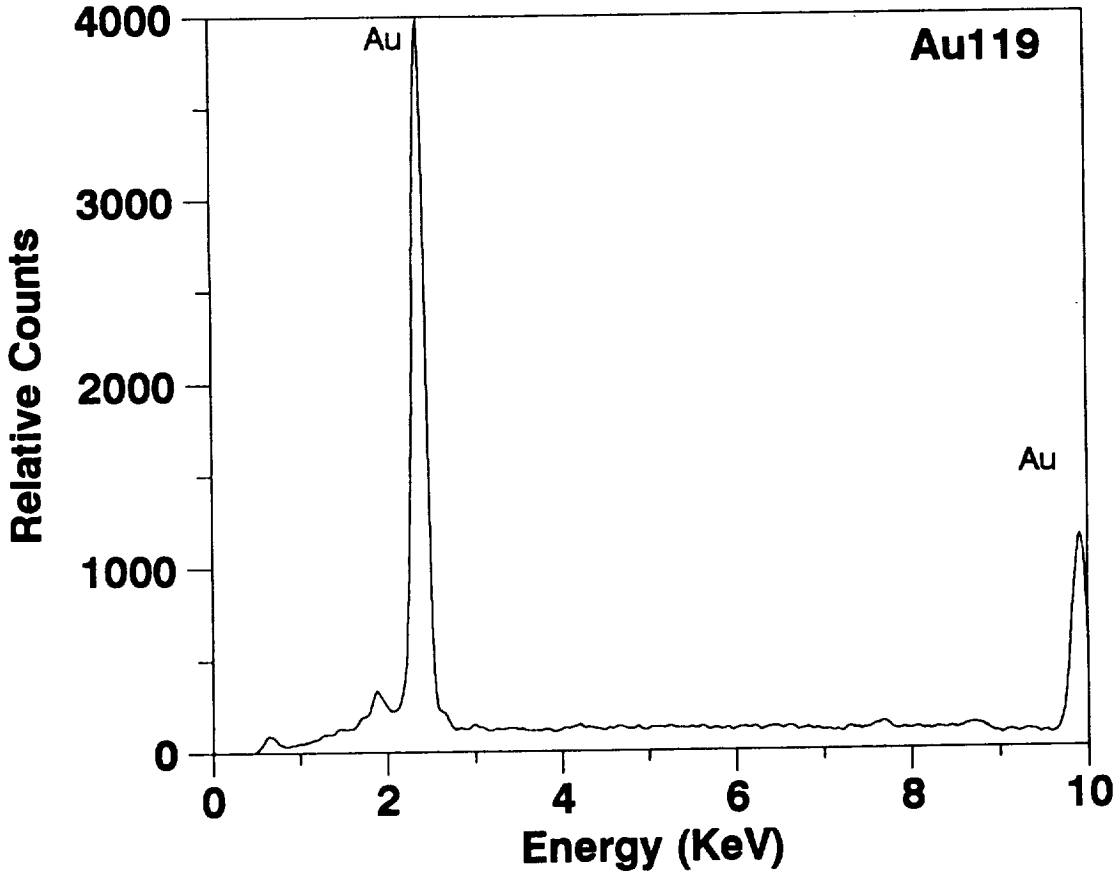


COMPONENT: EOOF
FEATURE: 119
CORE: LD-58

DIAMETER: 25 μm
ORIGIN: Unknown



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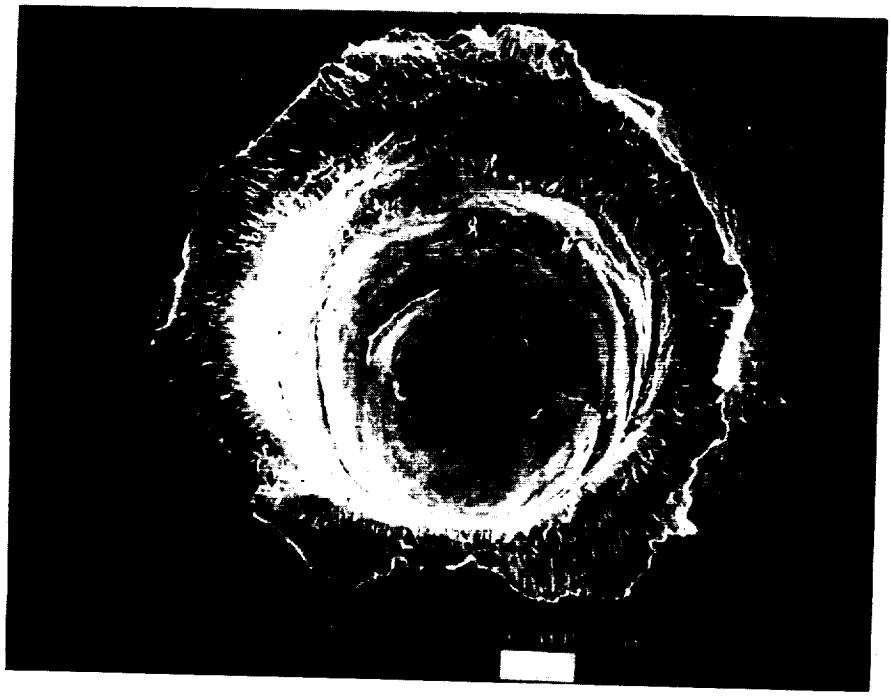
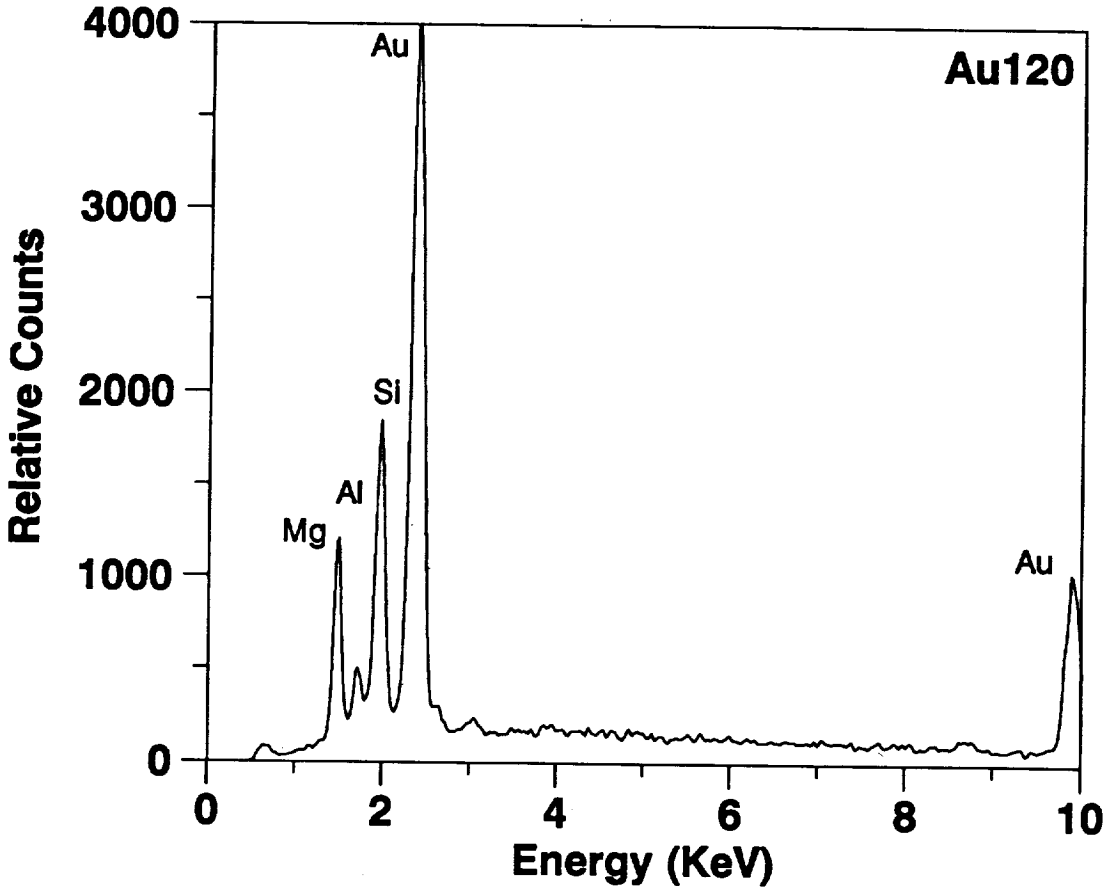


COMPONENT: EOOF
FEATURE: 120
CORE: LD-54

DIAMETER: 170 μm
ORIGIN: Natural



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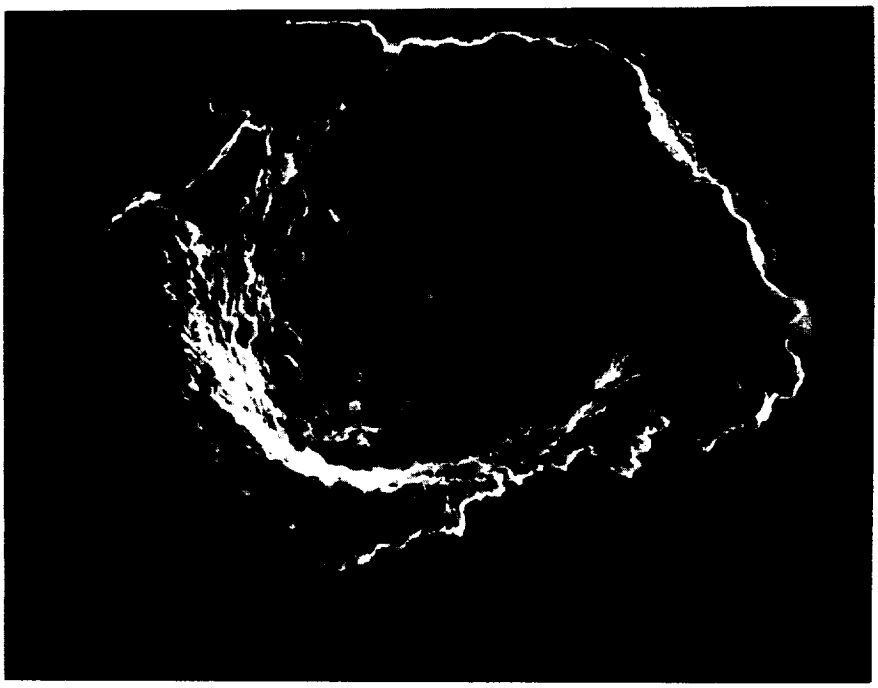
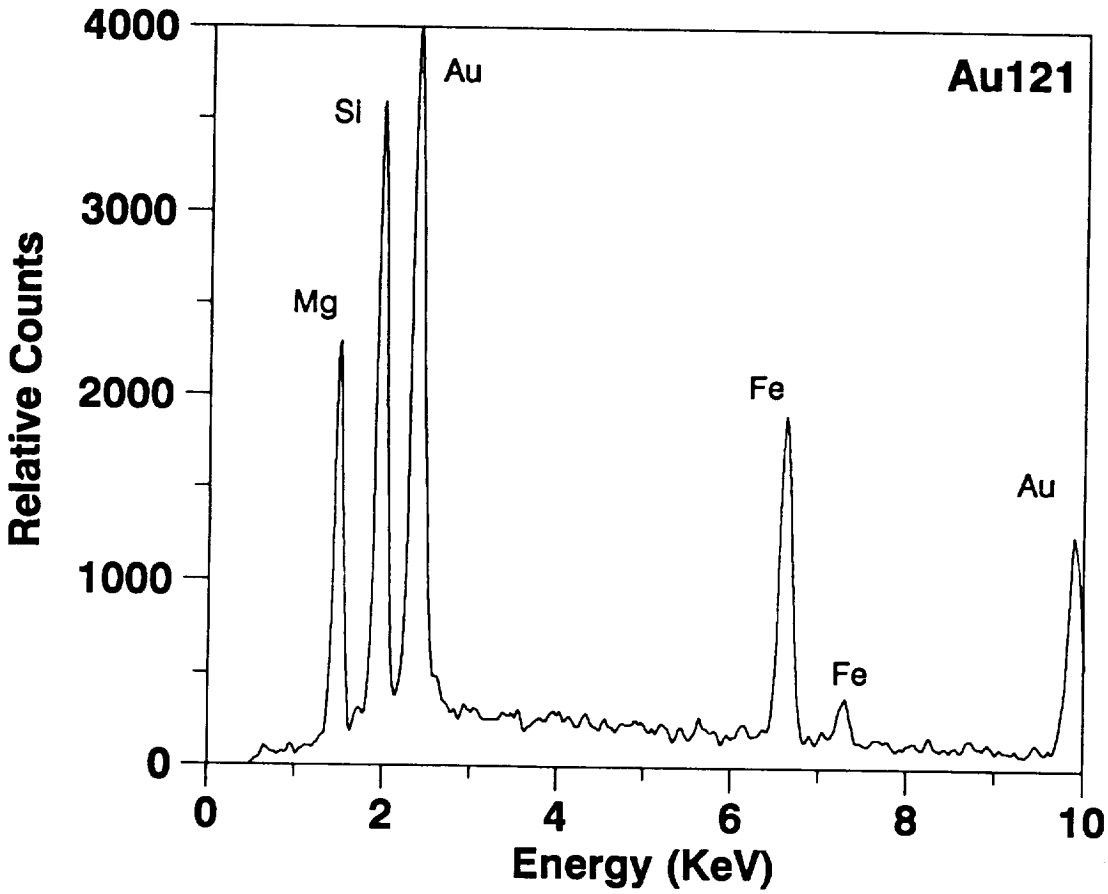


COMPONENT: EOOF
FEATURE: 121
CORE: LD-55

DIAMETER: 40 μm
ORIGIN: Natural



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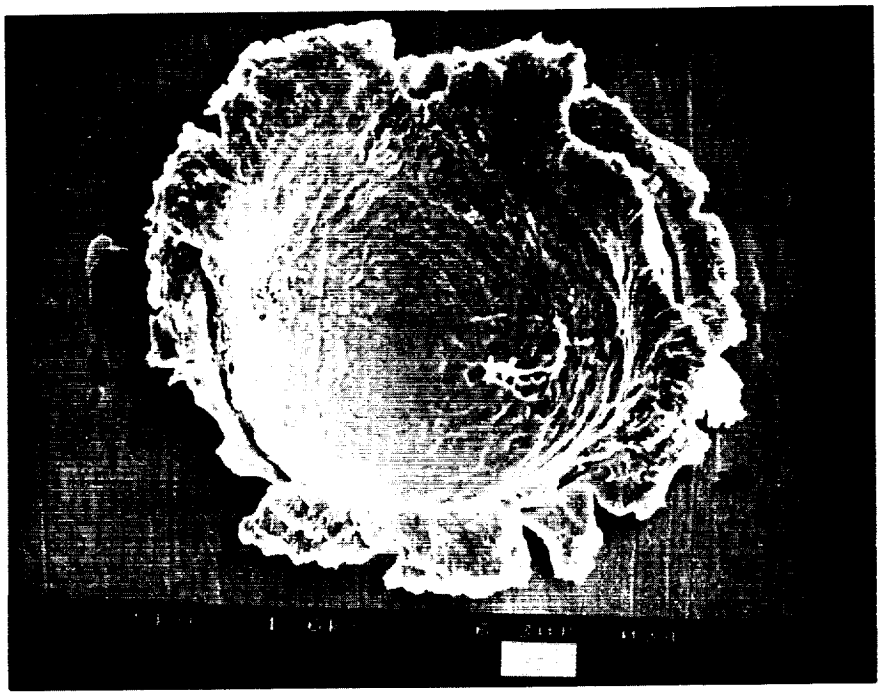
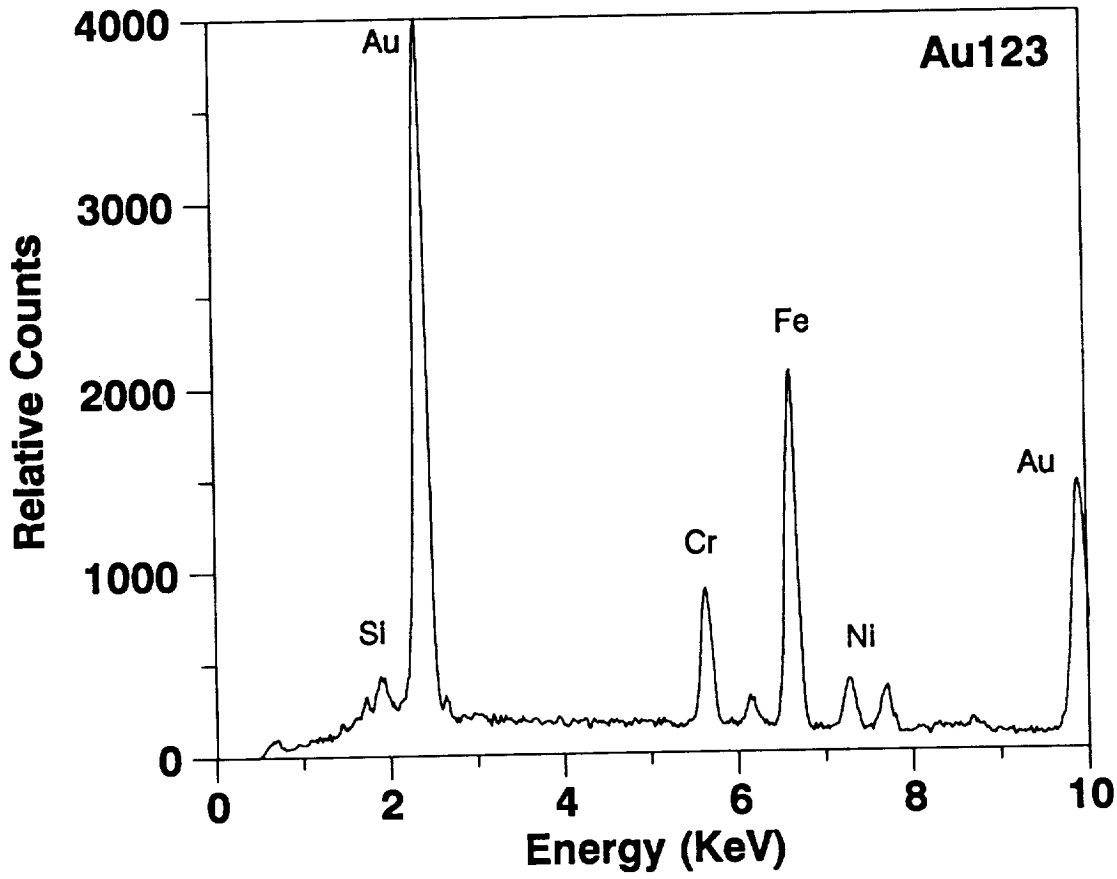


COMPONENT: EOOF
FEATURE: 123
CORE: LD-59

DIAMETER: 35 μm
ORIGIN: Man-made



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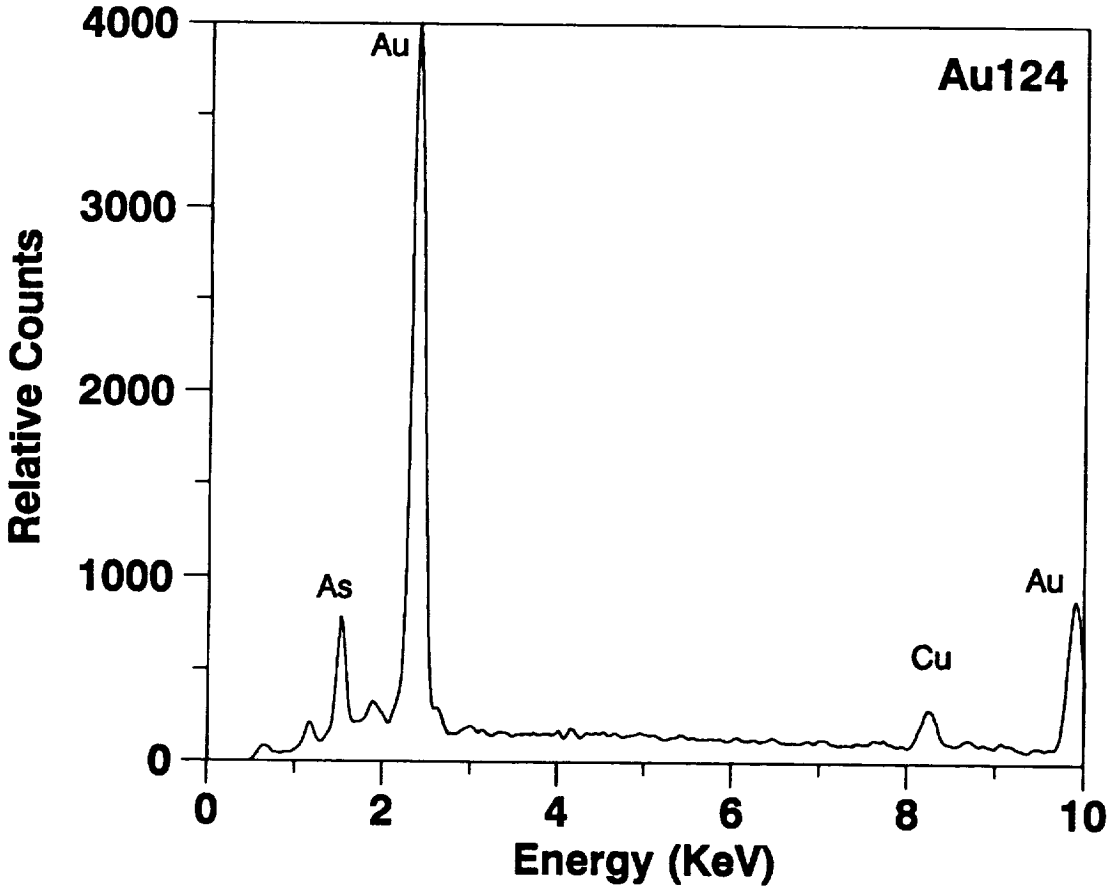
COMPONENT: EOOF
FEATURE: 124
CORE: LD-61

DIAMETER: 20 μm
ORIGIN: Unknown



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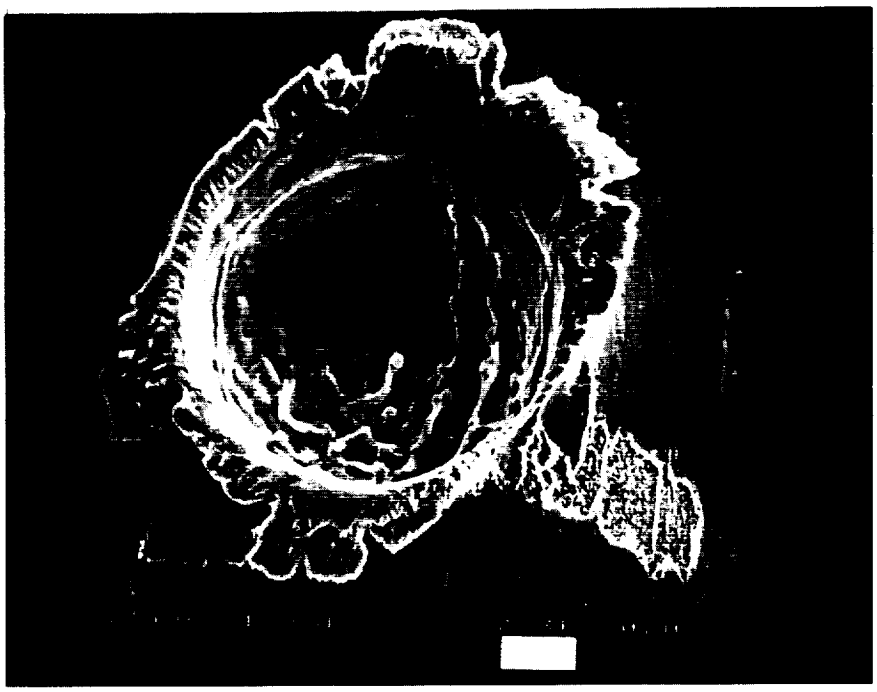
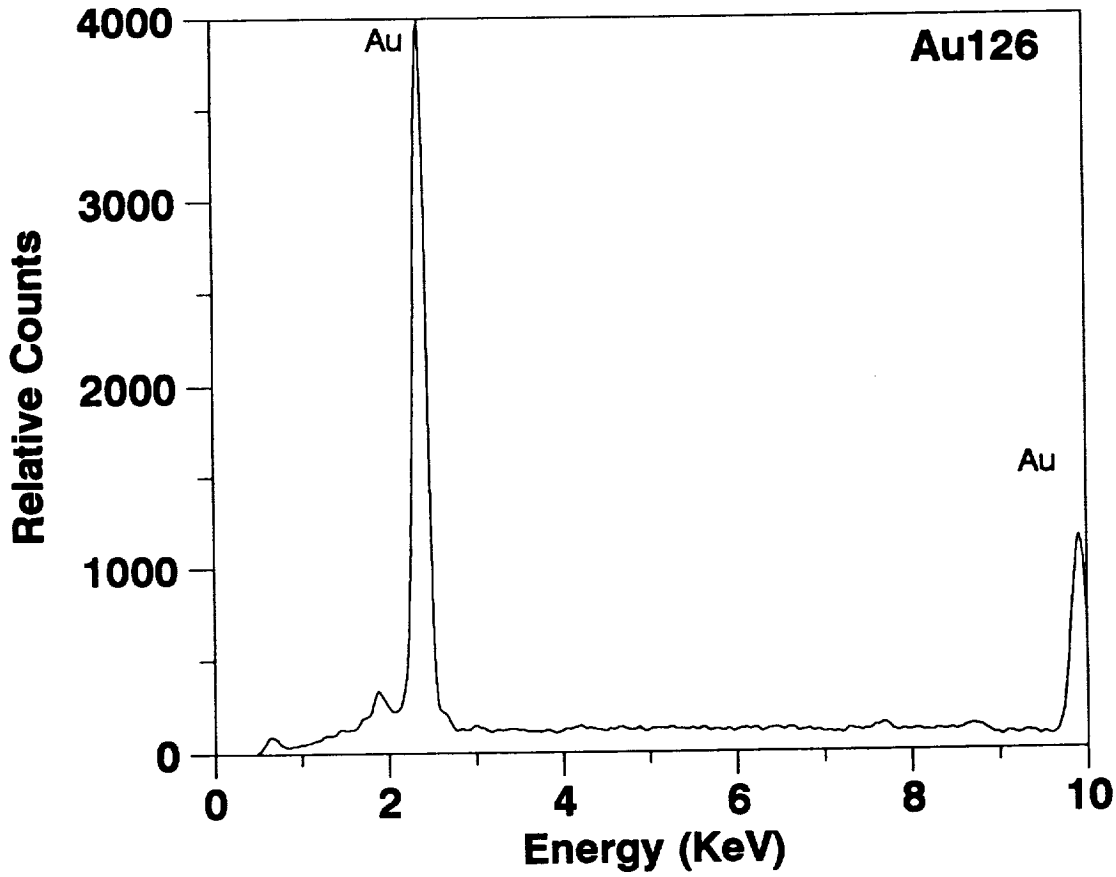


COMPONENT: EOOF
FEATURE: 126
CORE: LD-80

DIAMETER: 30 μm
ORIGIN: Unknown



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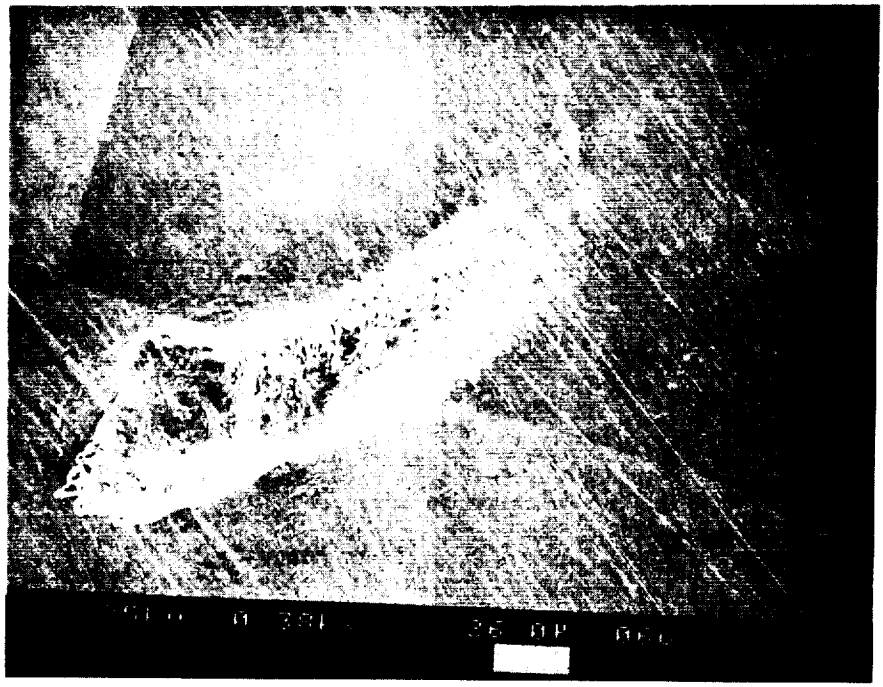
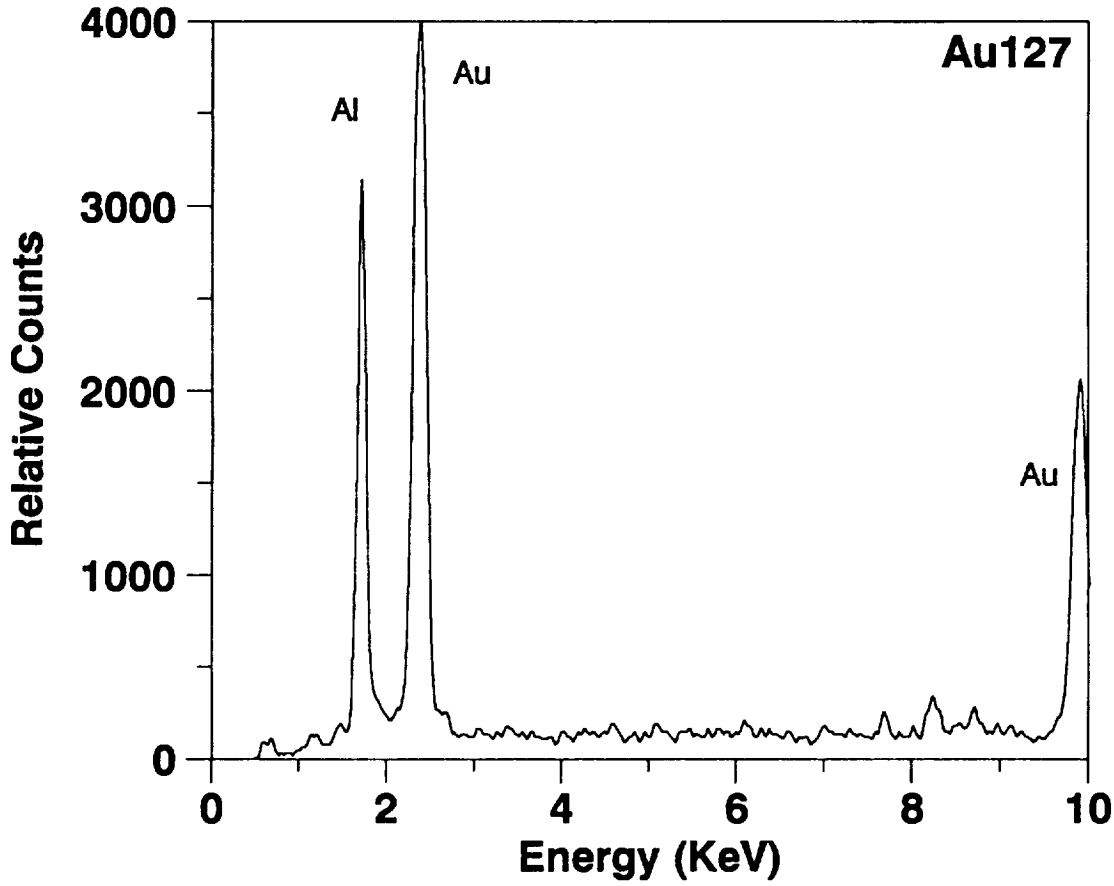


COMPONENT: EOOF
FEATURE: 127
CORE: LD-78

DIAMETER: 150 μm
ORIGIN: Man-made



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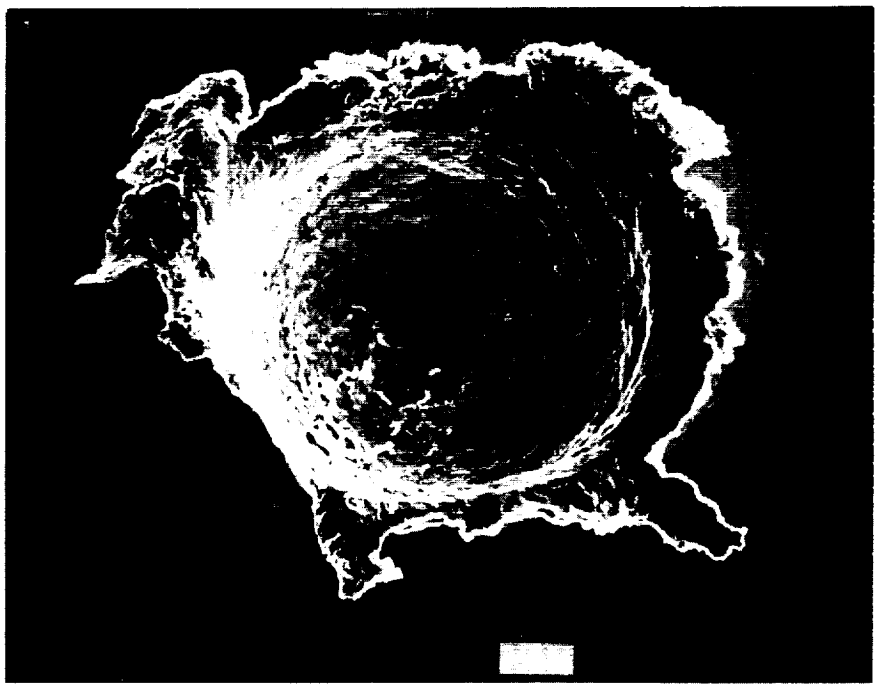
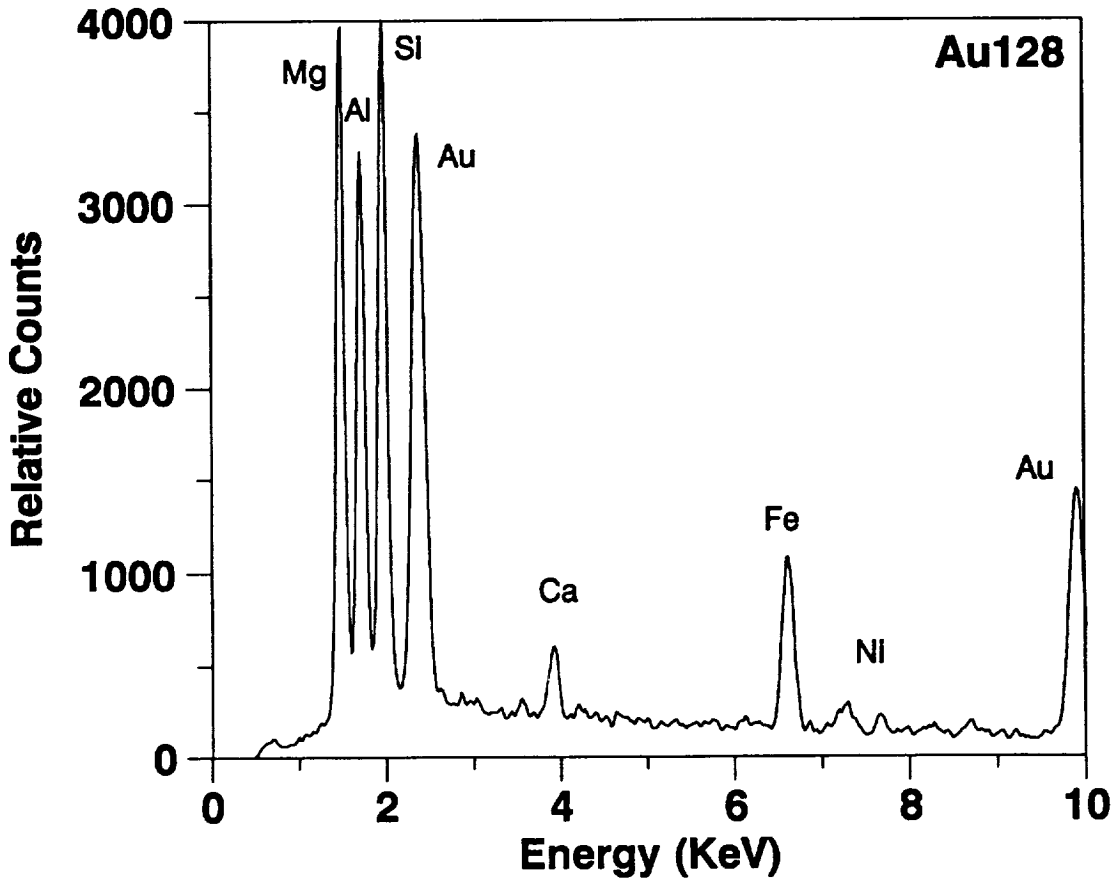


COMPONENT: EOOF
FEATURE: 128
CORE: LD-79

DIAMETER: 55 μm
ORIGIN: Natural



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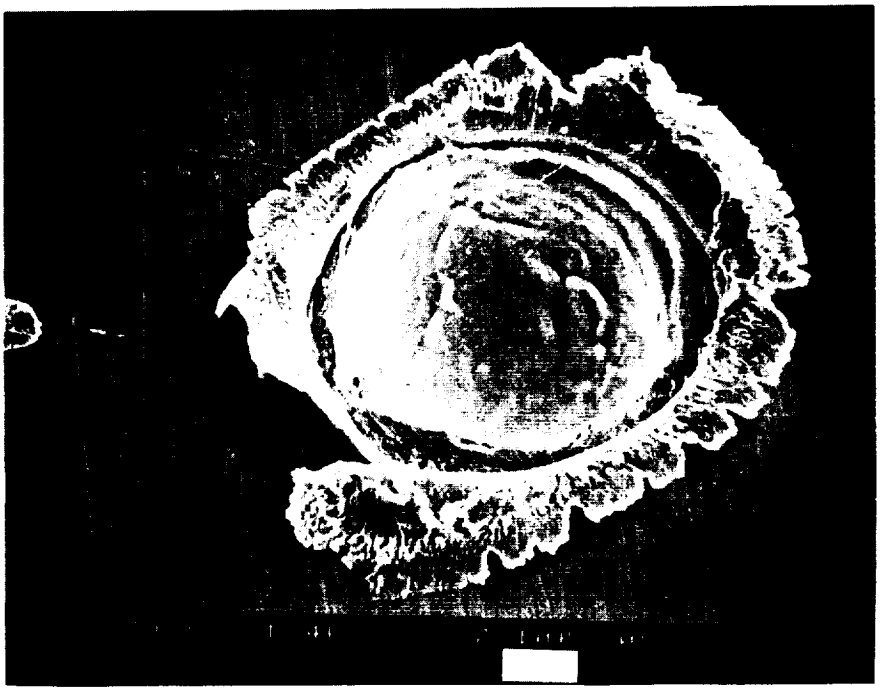
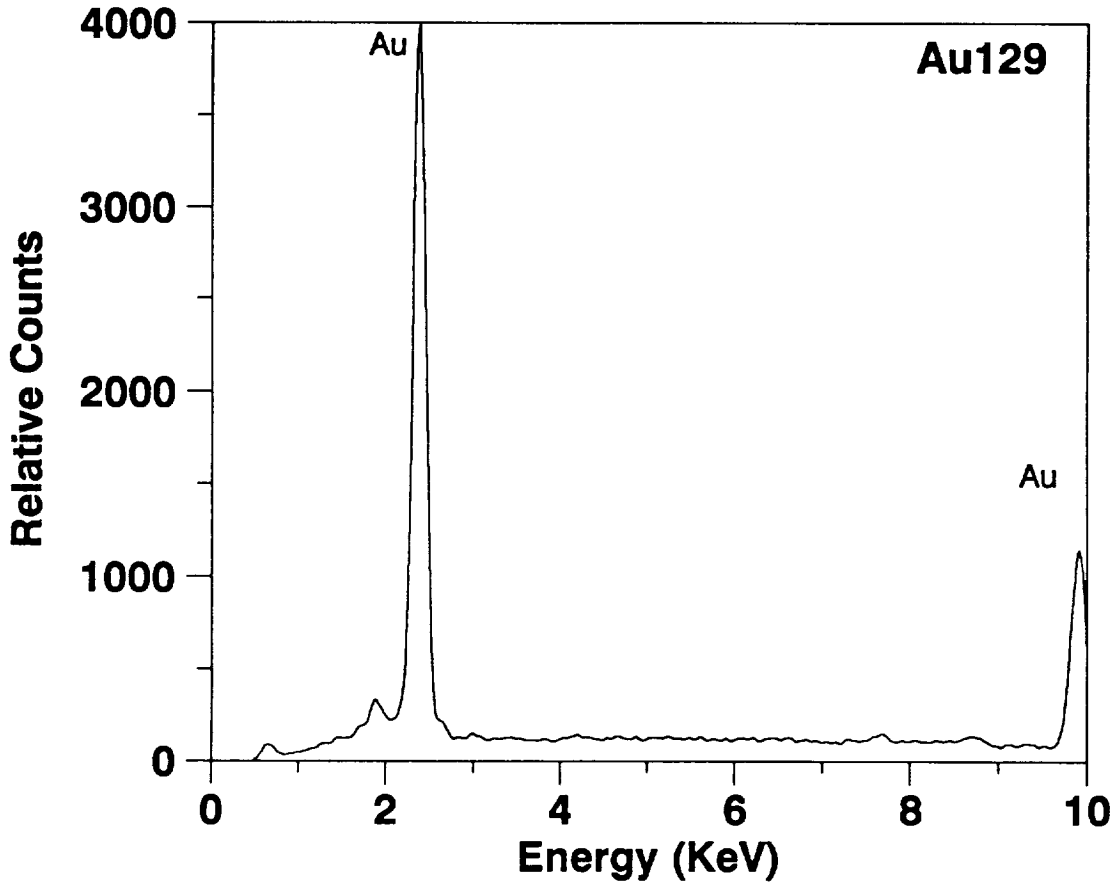


COMPONENT: EOOF
FEATURE: 129
CORE: LD-73

DIAMETER: 35 μm
ORIGIN: Unknown



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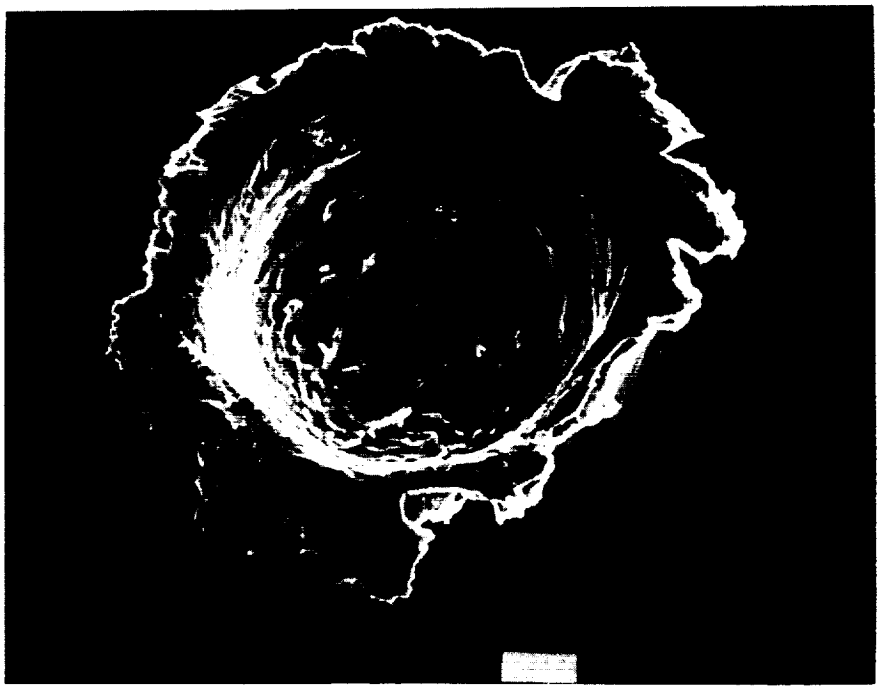
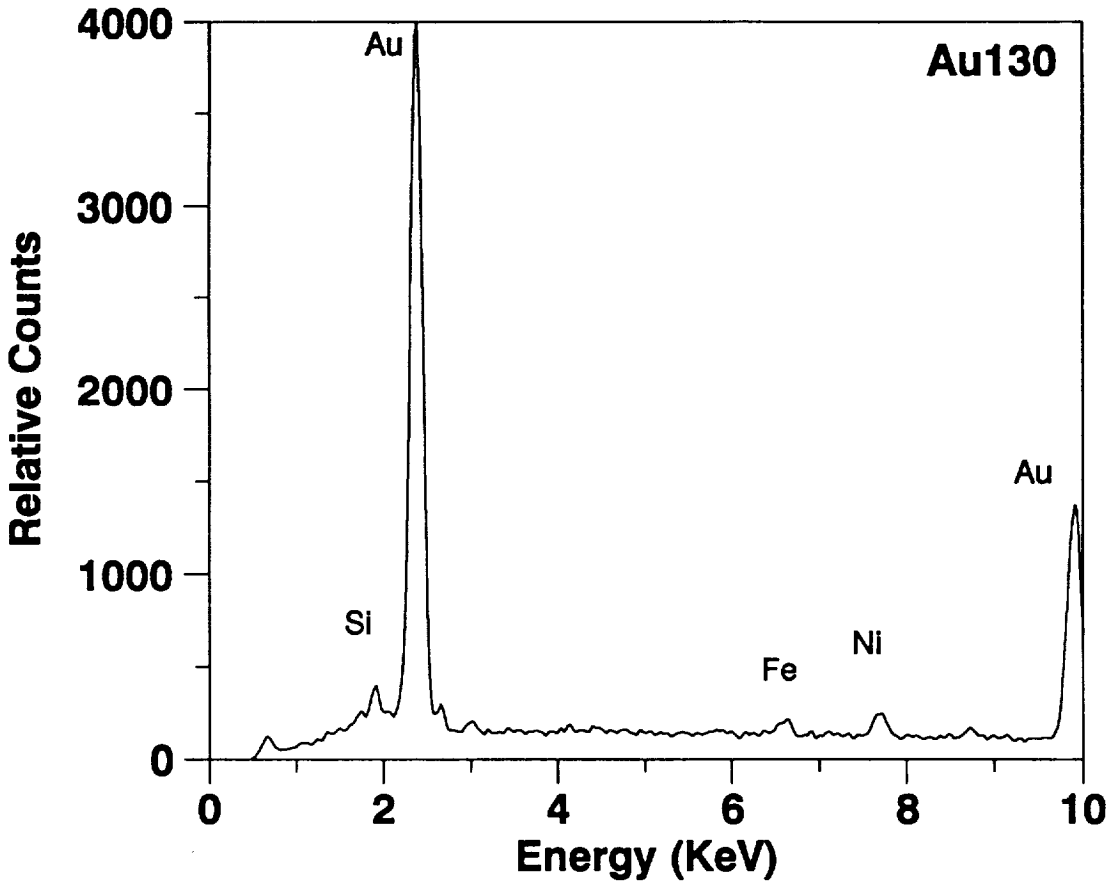


COMPONENT: EOOF
FEATURE: 130
CORE: LD-77

DIAMETER: 55 μm
ORIGIN: Natural



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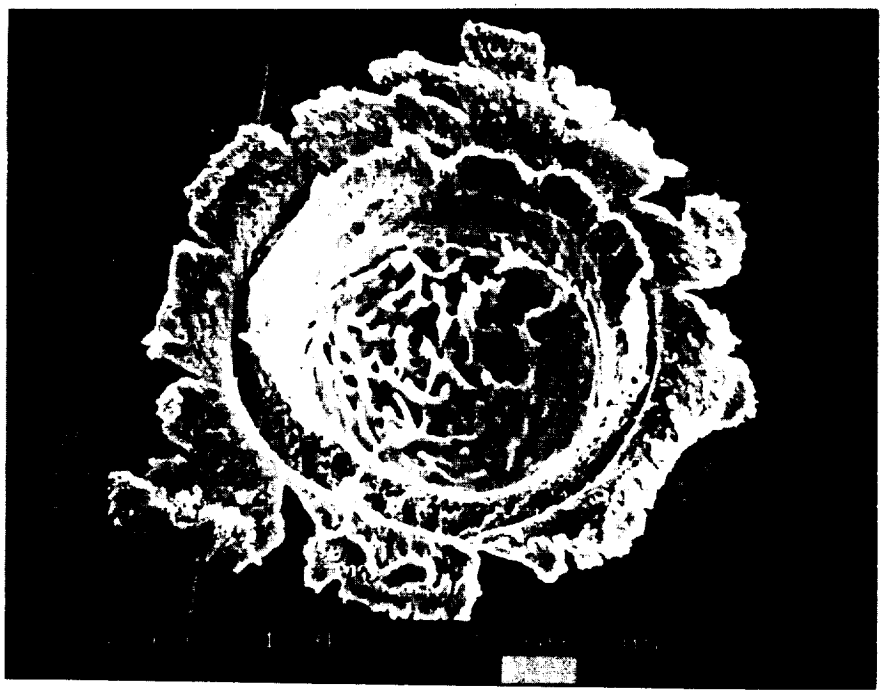
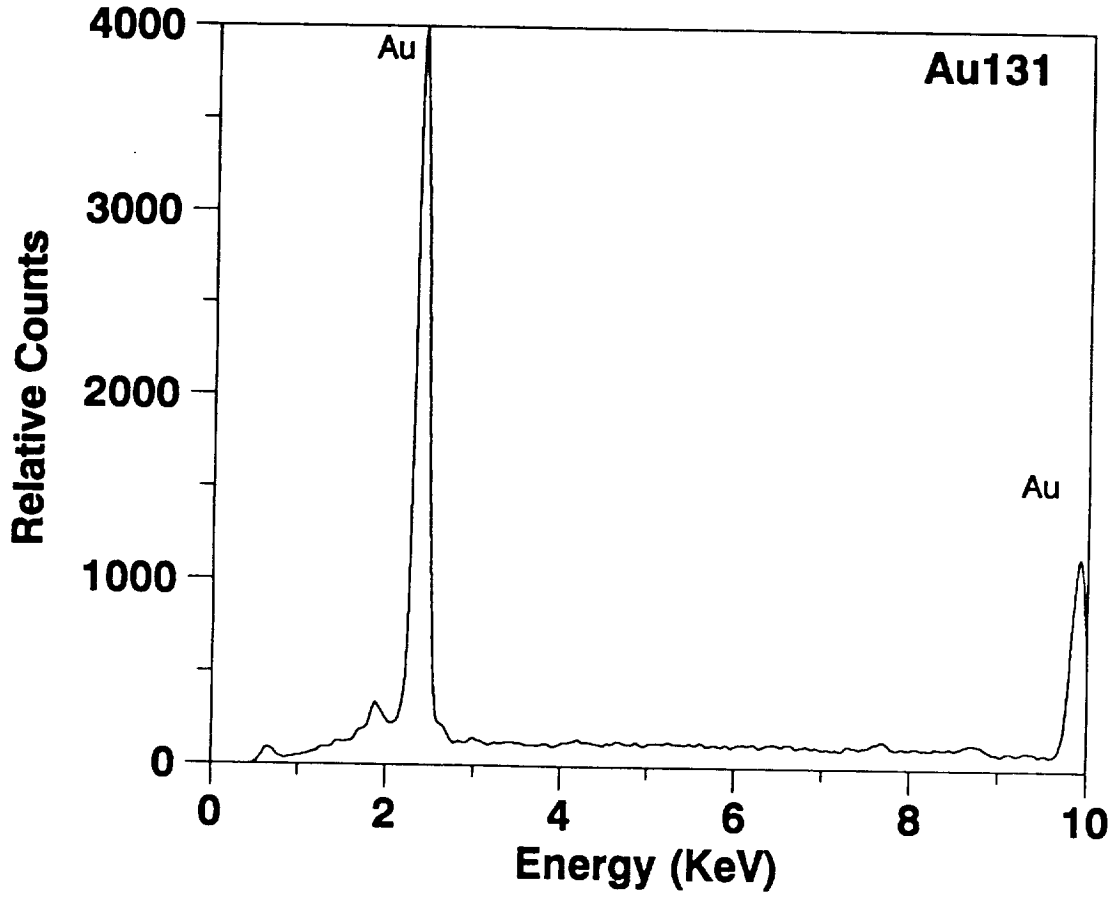


COMPONENT: EOOF
FEATURE: 131
CORE: LD-72

DIAMETER: 25 μm
ORIGIN: Unknown



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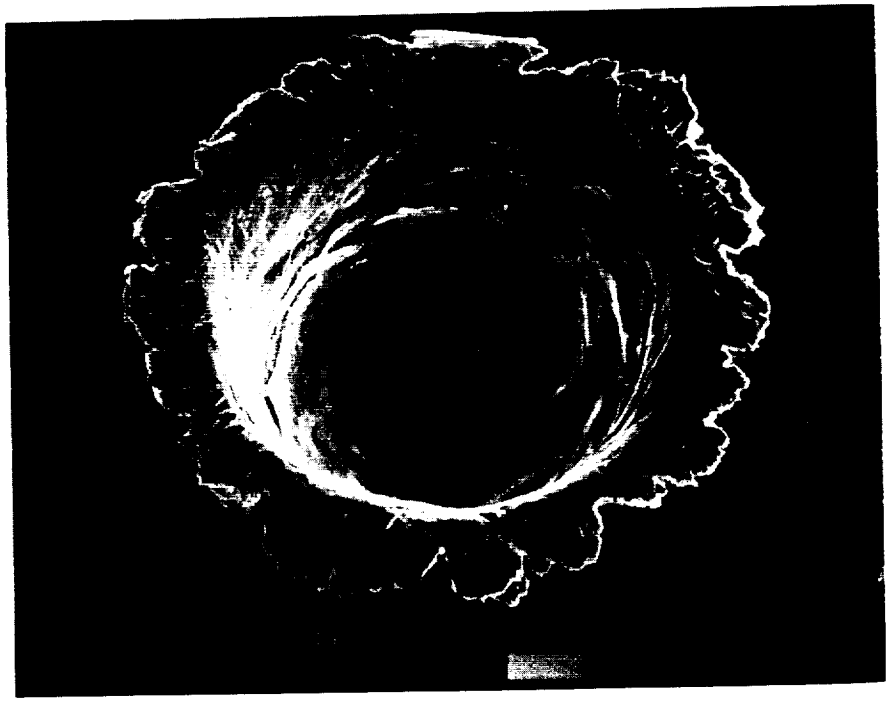
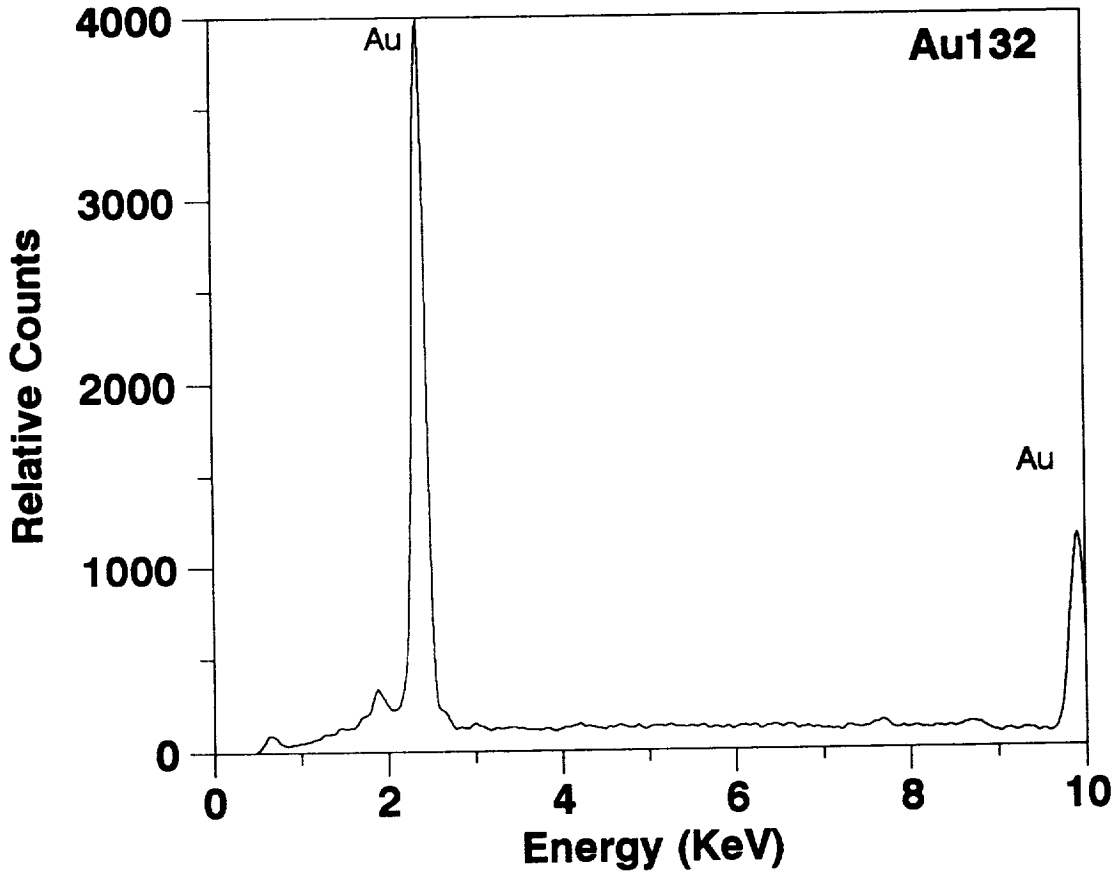


COMPONENT: EOOF
FEATURE: 132
CORE: LD-74

DIAMETER: 65 μm
ORIGIN: Unknown



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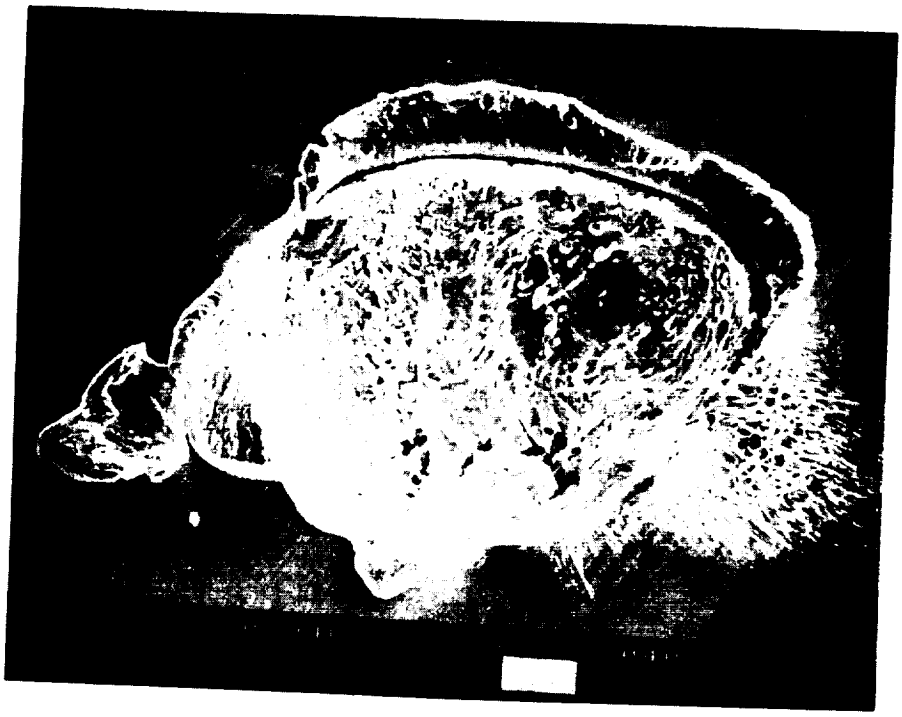
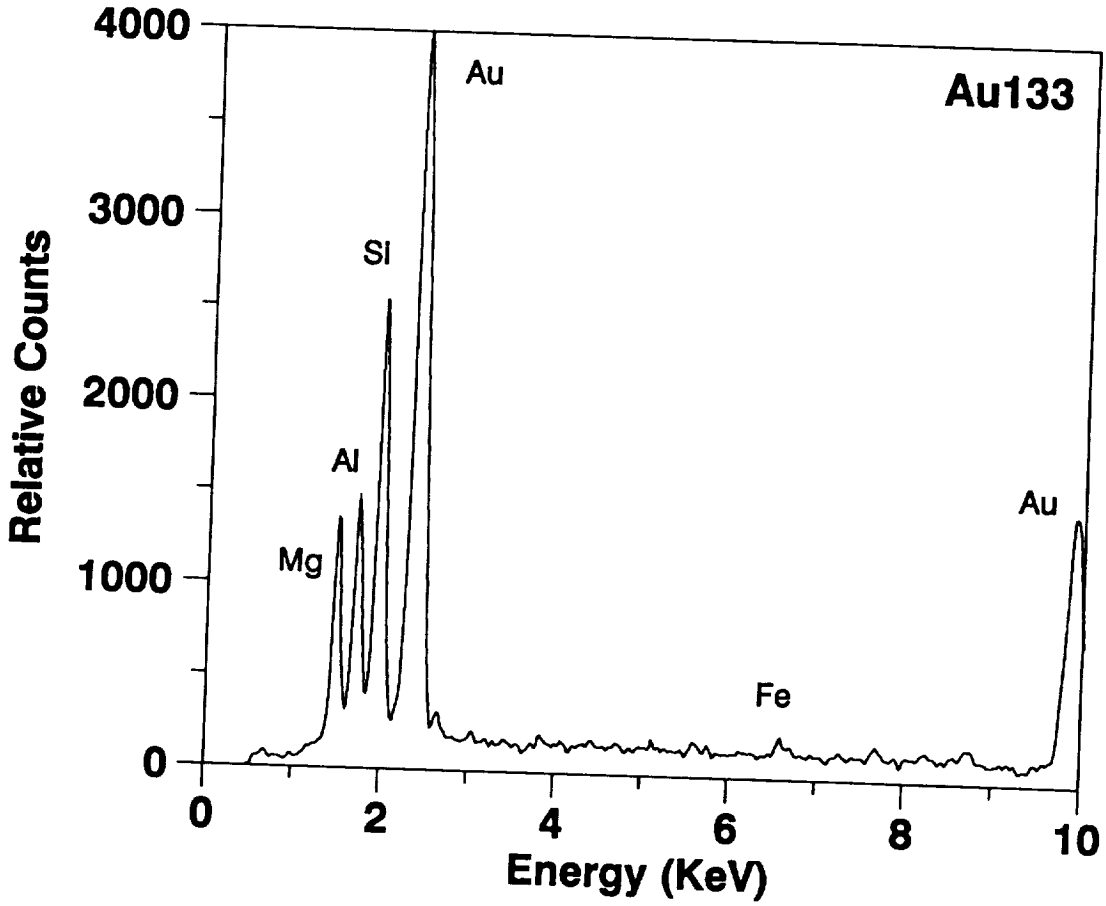


COMPONENT: EOOF
FEATURE: 133
CORE: LD-63

DIAMETER: 85 μm
ORIGIN: Natural



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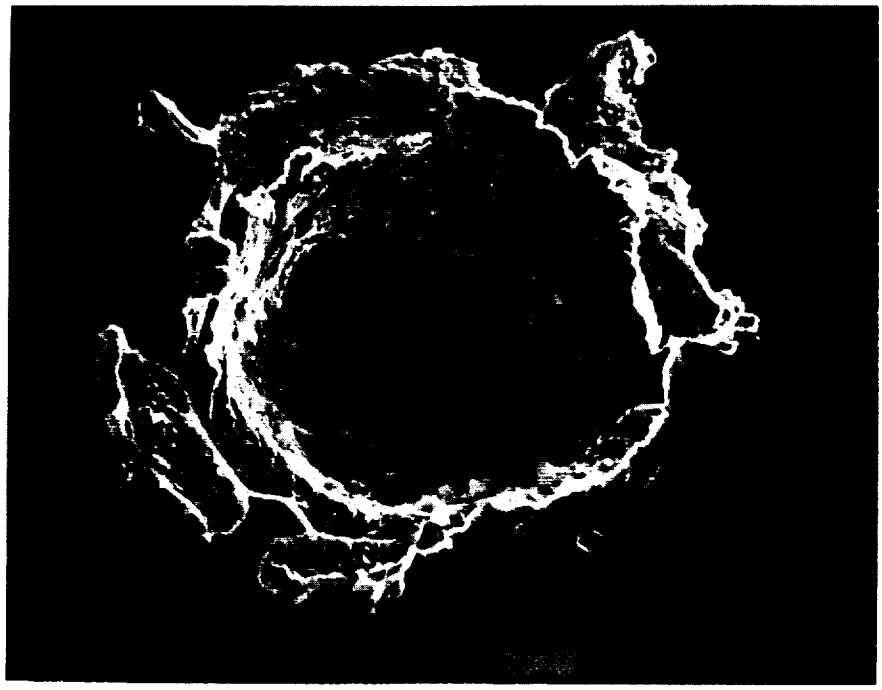
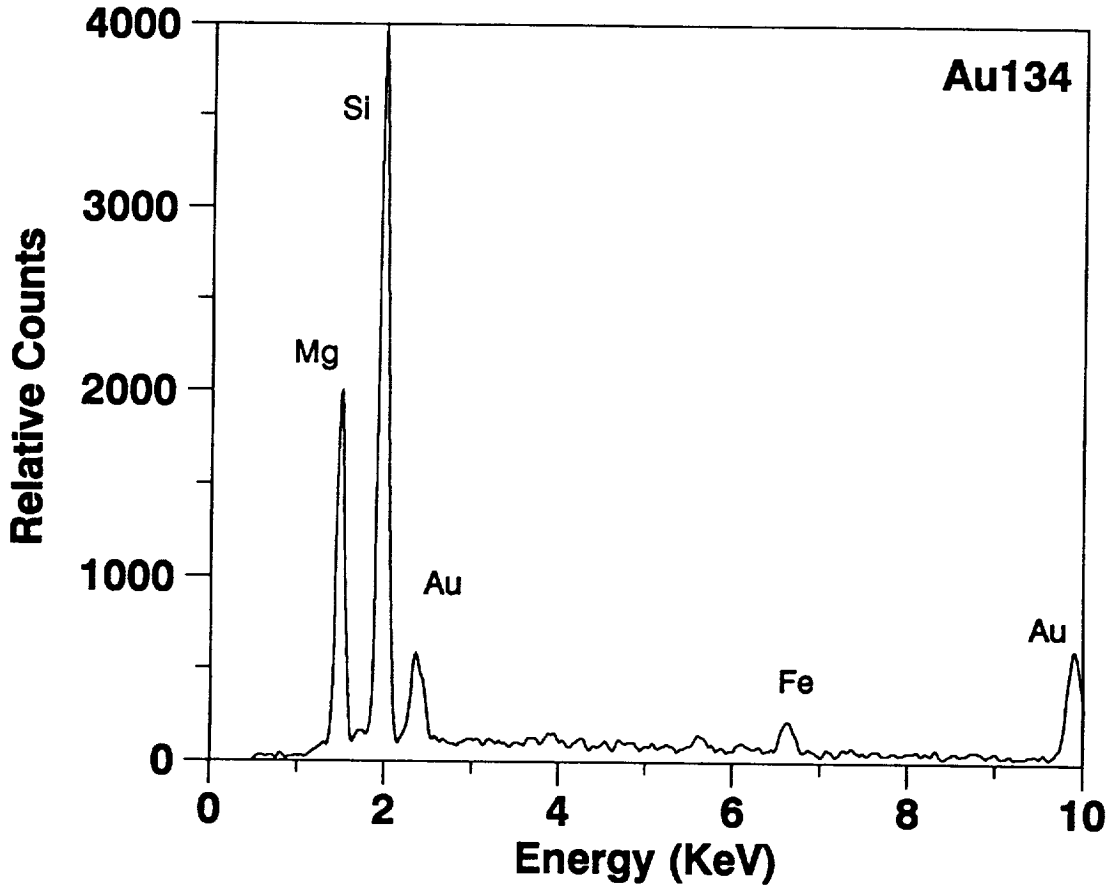


COMPONENT: EOOF
FEATURE: 134
CORE: LD-71

DIAMETER: 55 μm
ORIGIN: Natural



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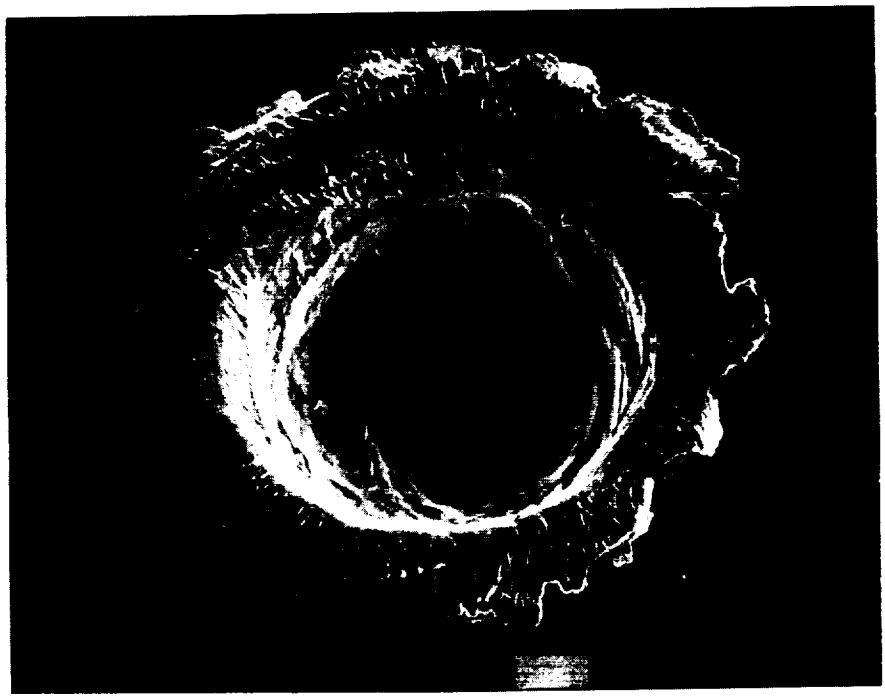
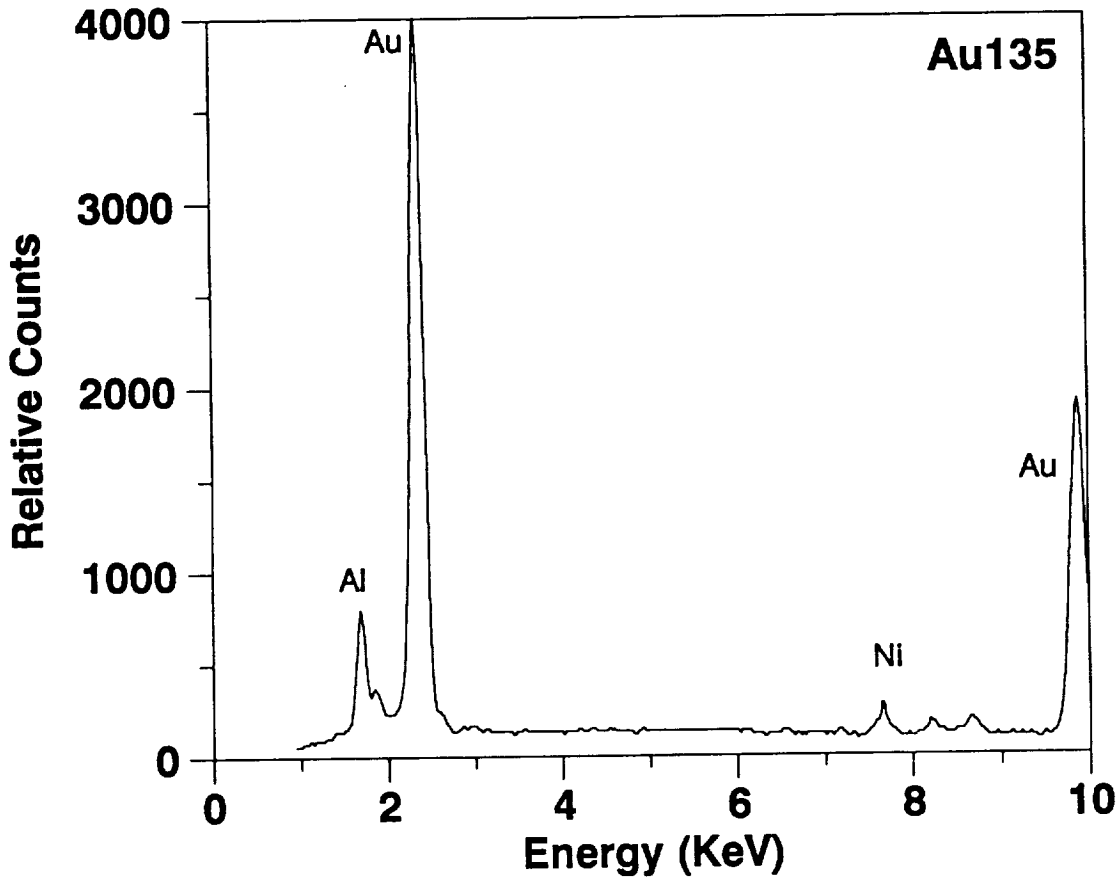


COMPONENT: EOOF
FEATURE: 135
CORE: LD-62

DIAMETER: 160 μm
ORIGIN: Man-made



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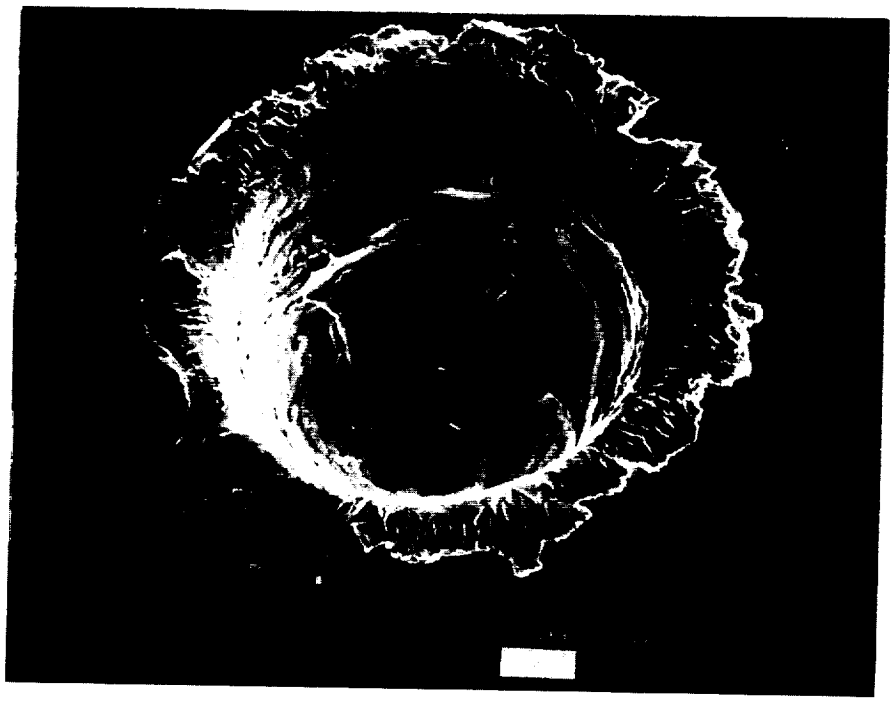
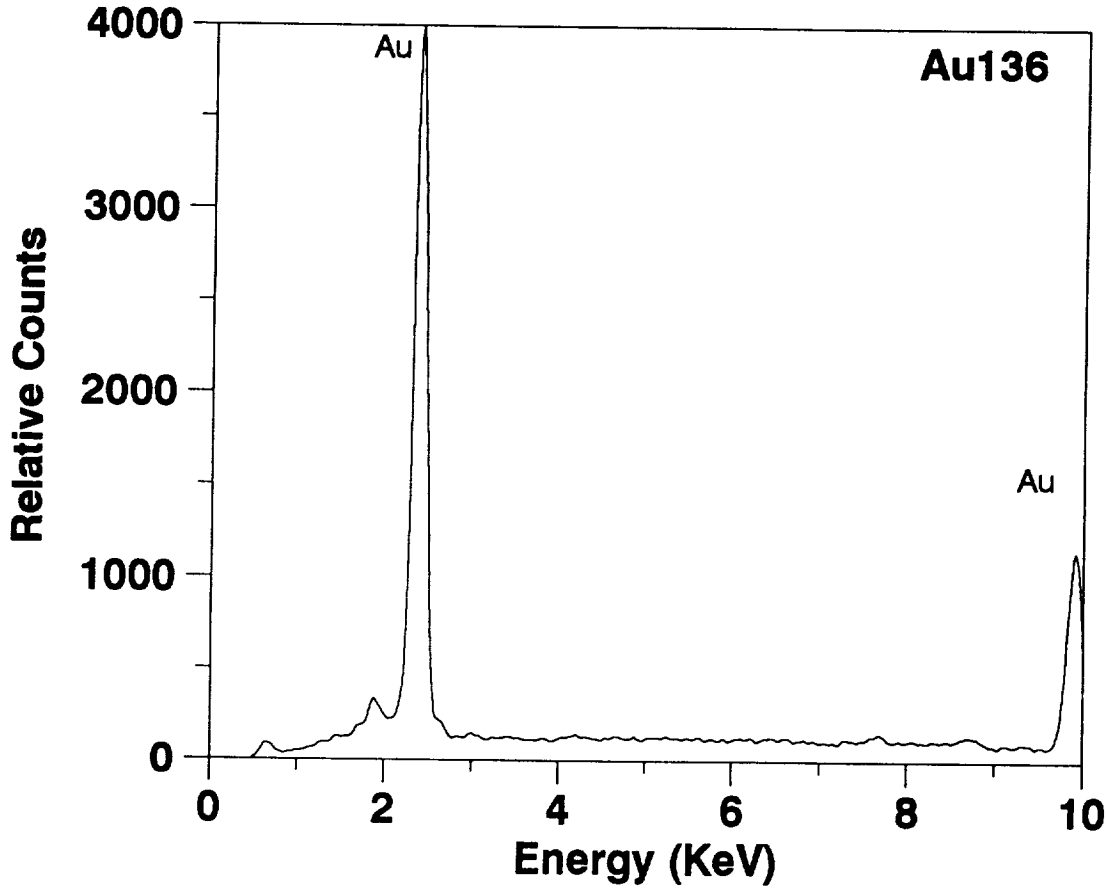


COMPONENT: EOOF
FEATURE: 136
CORE: LD-76

DIAMETER: 105 μm
ORIGIN: Unknown



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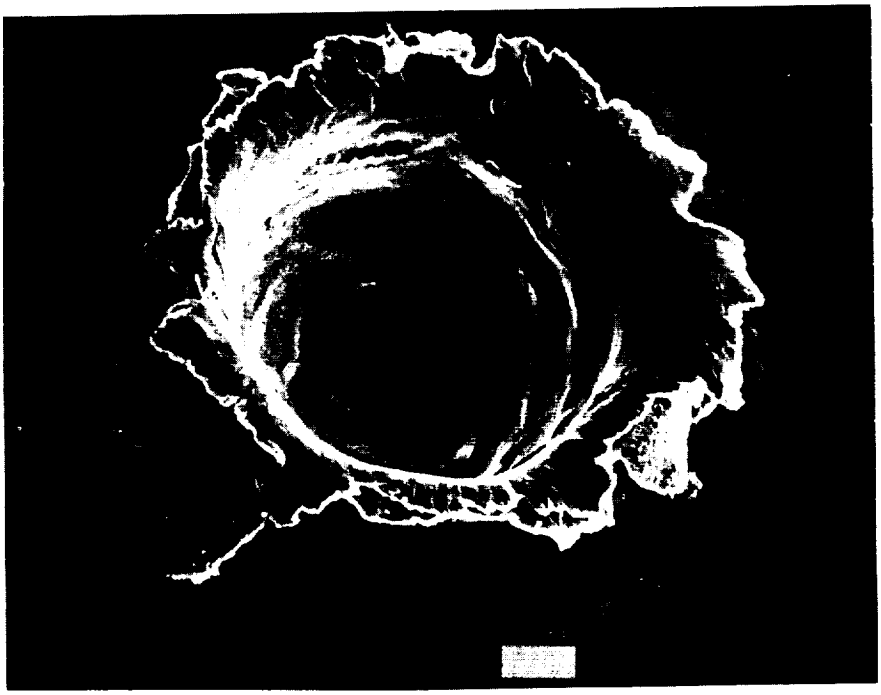
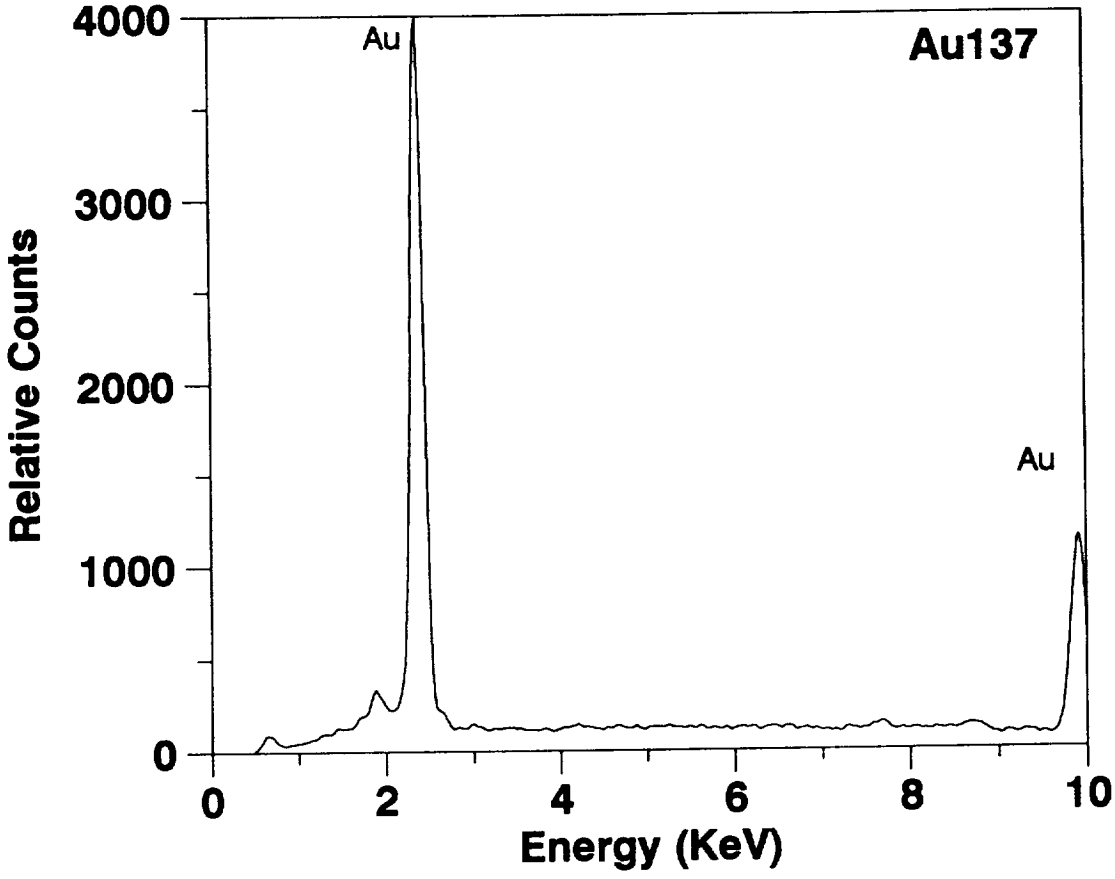


COMPONENT: EOOF
FEATURE: 137
CORE: LD-75

DIAMETER: 40 μm
ORIGIN: Unknown



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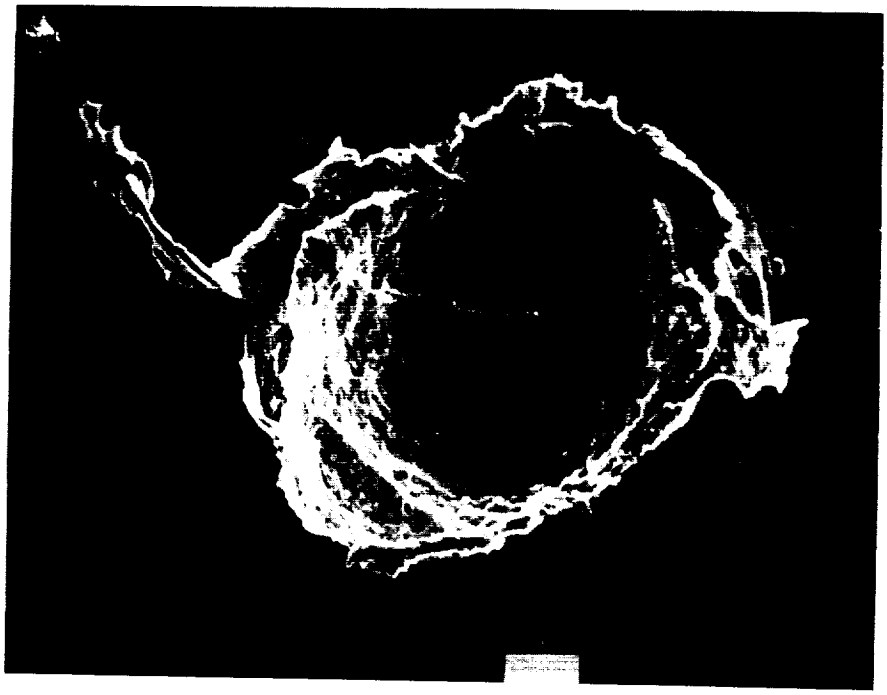
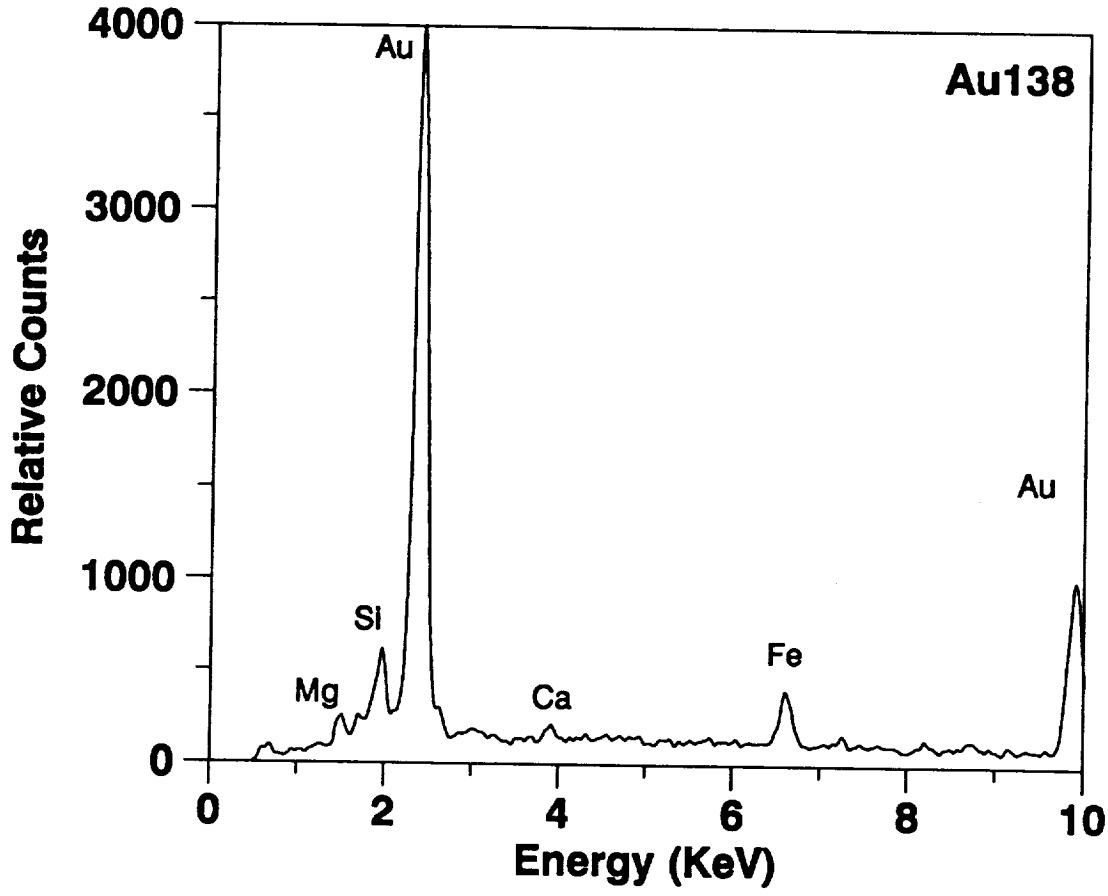


COMPONENT: EOOF
FEATURE: 138
CORE: LD-70

DIAMETER: 60 μm
ORIGIN: Natural



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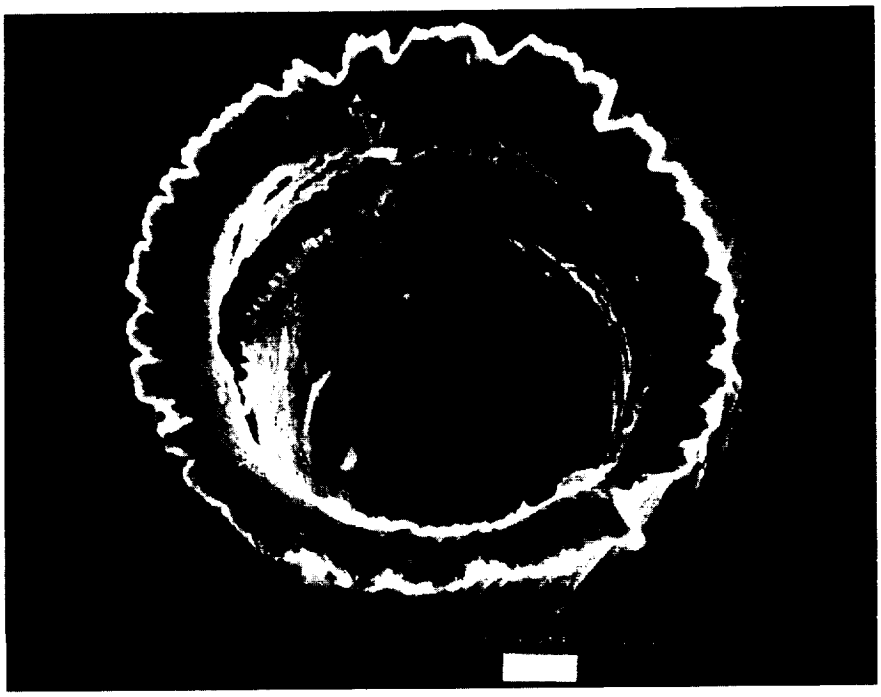
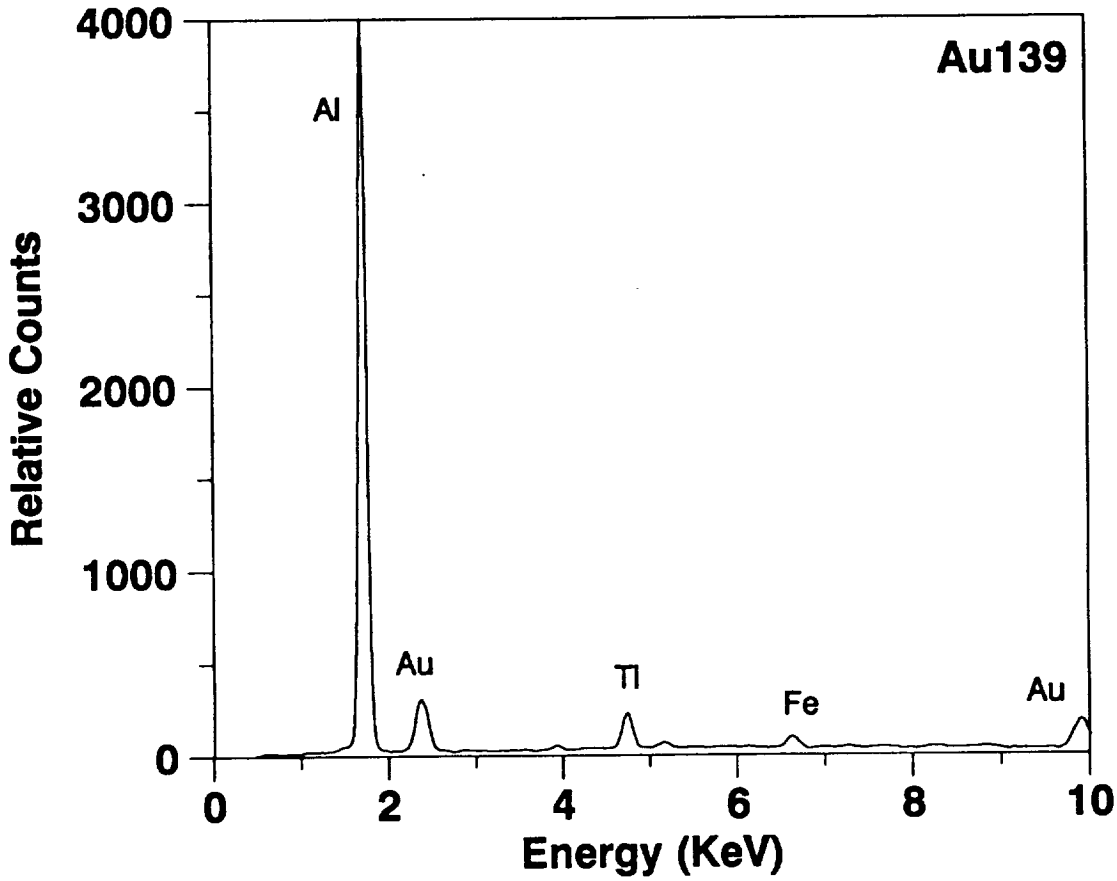


COMPONENT: EOOF
FEATURE: 139
CORE: LD-64

DIAMETER: 15 μm
ORIGIN: Man-made



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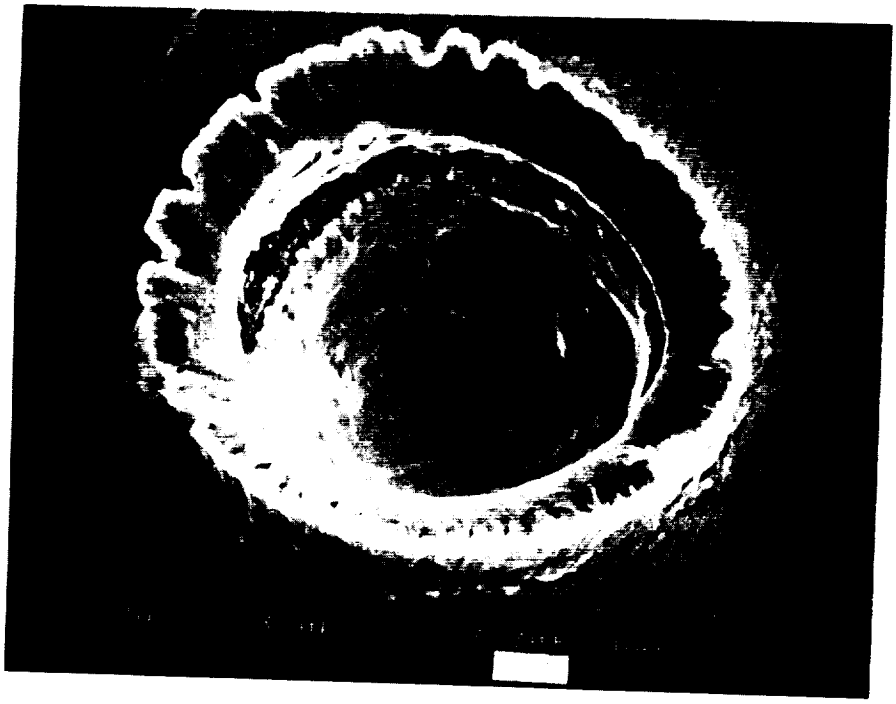
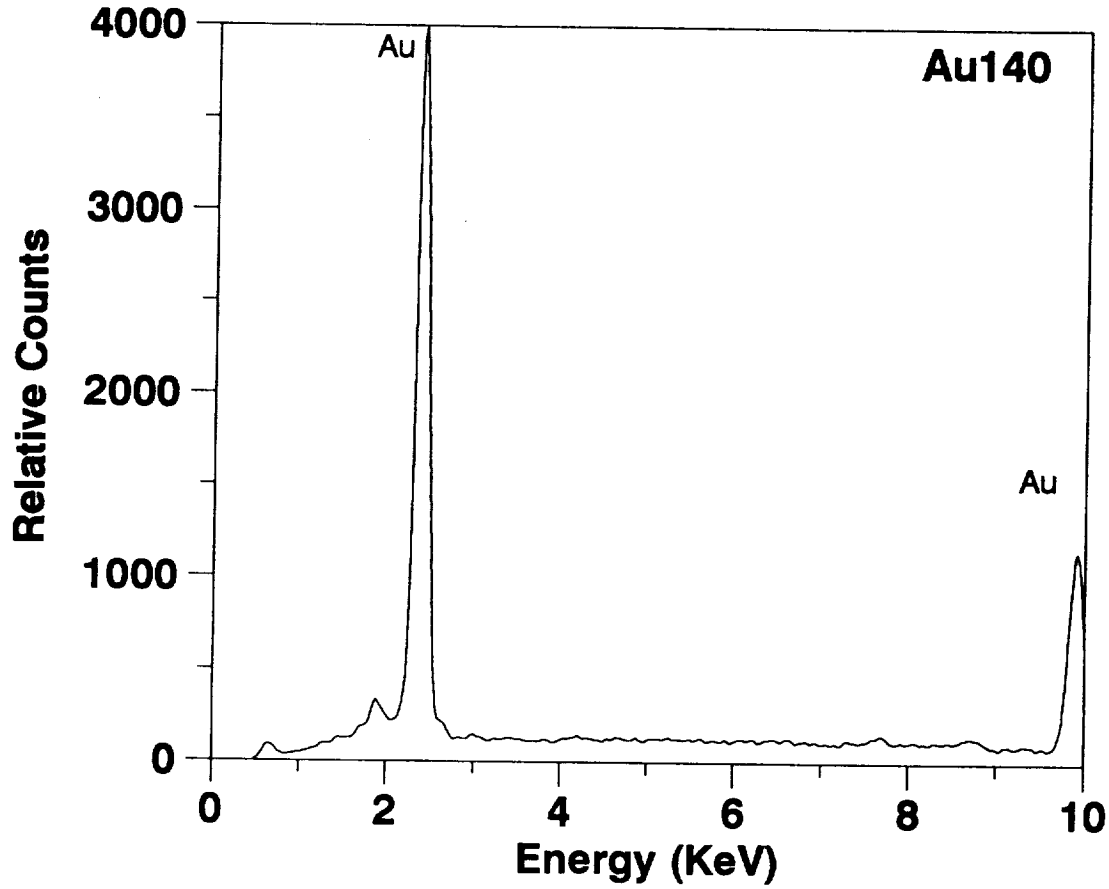


COMPONENT: EOOF
FEATURE: 140
CORE: LD-65

DIAMETER: 10 μm
ORIGIN: Unknown



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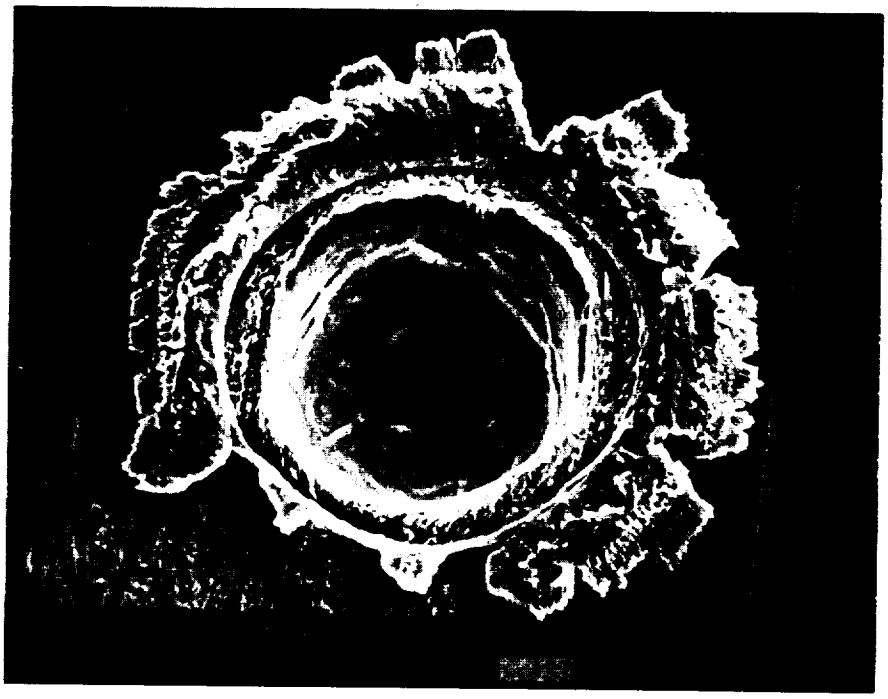
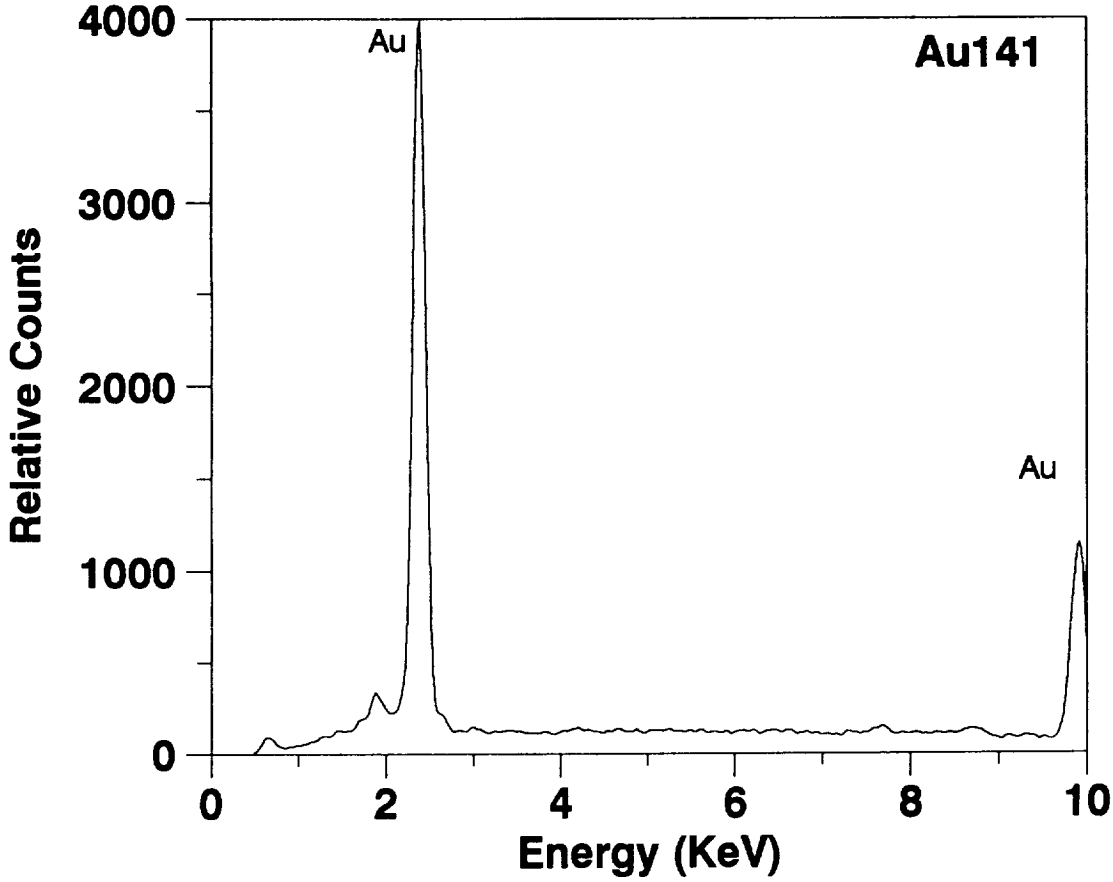


COMPONENT: EOOF
FEATURE: 141
CORE: LD-68

DIAMETER: 40 μm
ORIGIN: Unknown



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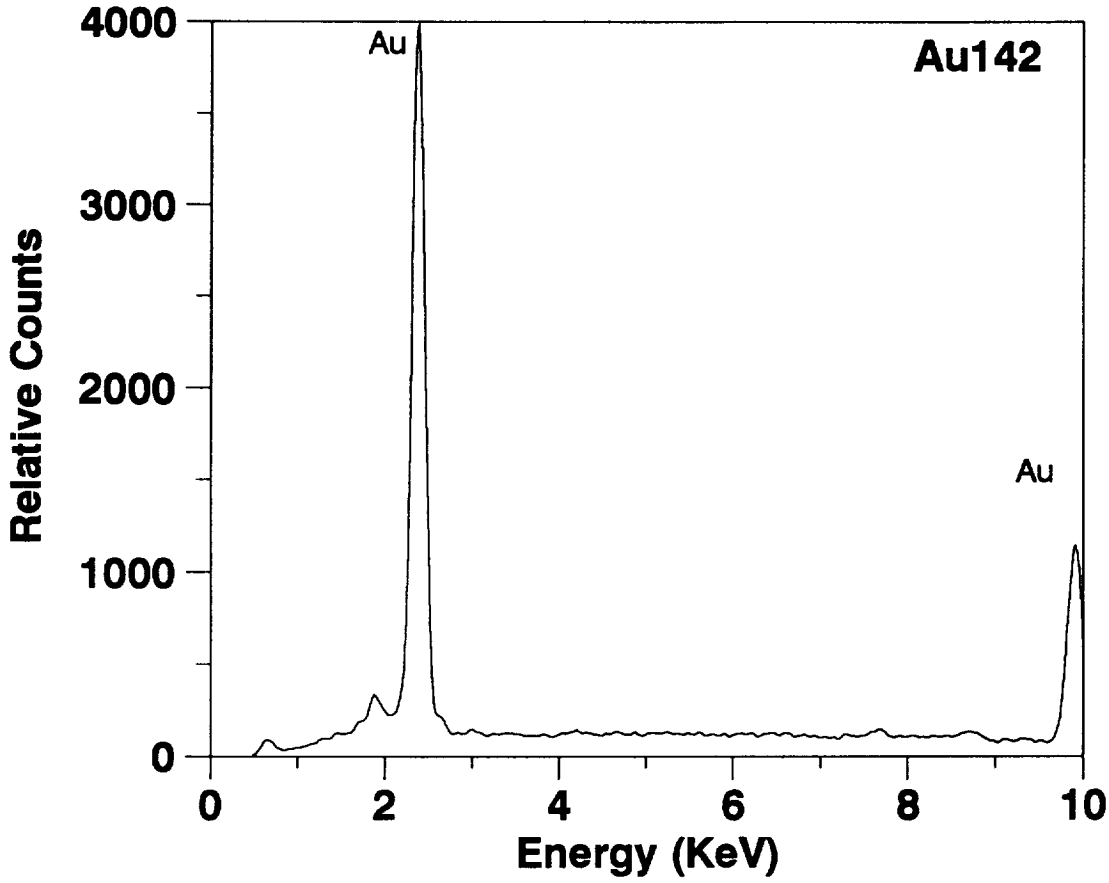
COMPONENT: EOOF
FEATURE: 142
CORE: LD-69

DIAMETER: 20 μm
ORIGIN: Unknown



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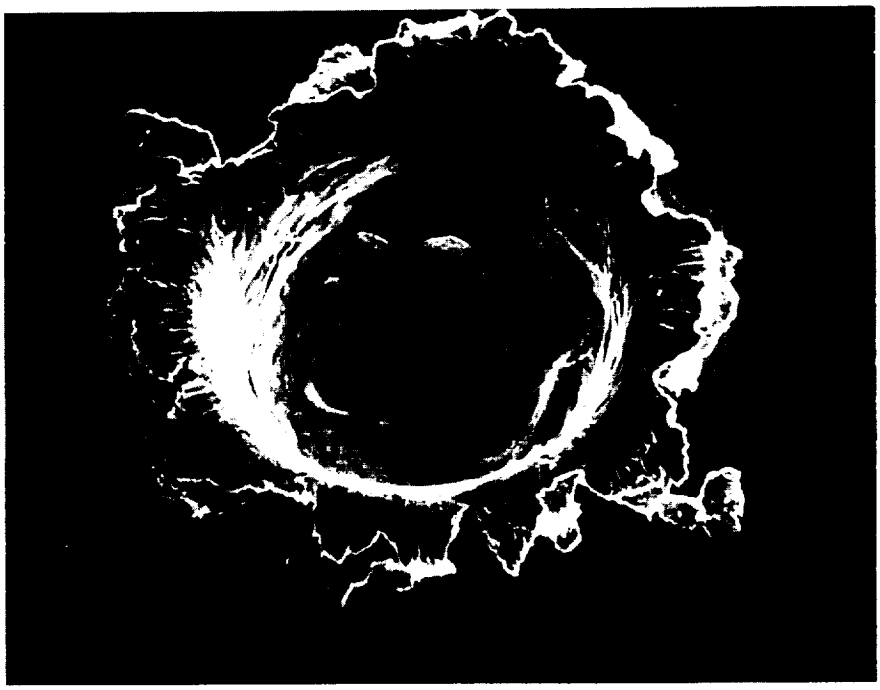
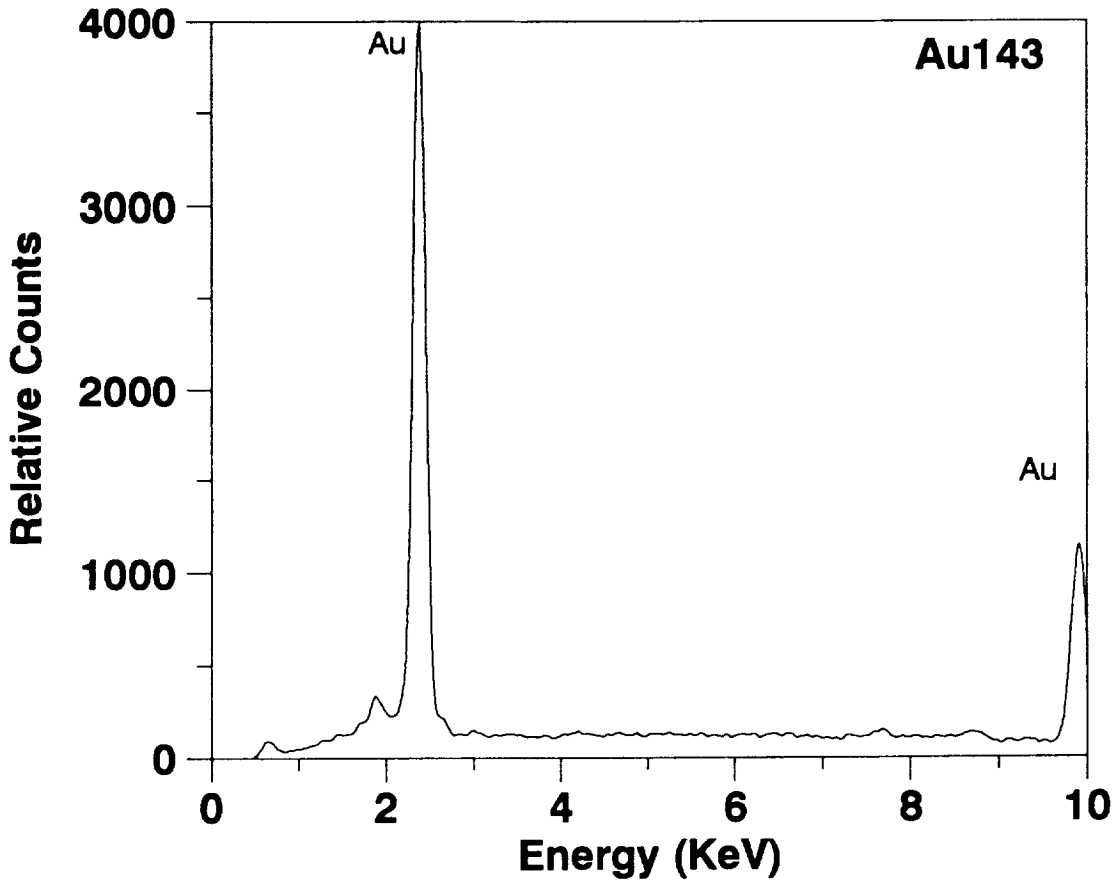


COMPONENT: EOOF
FEATURE: 143
CORE: LD-67

DIAMETER: 65 μm
ORIGIN: Unknown



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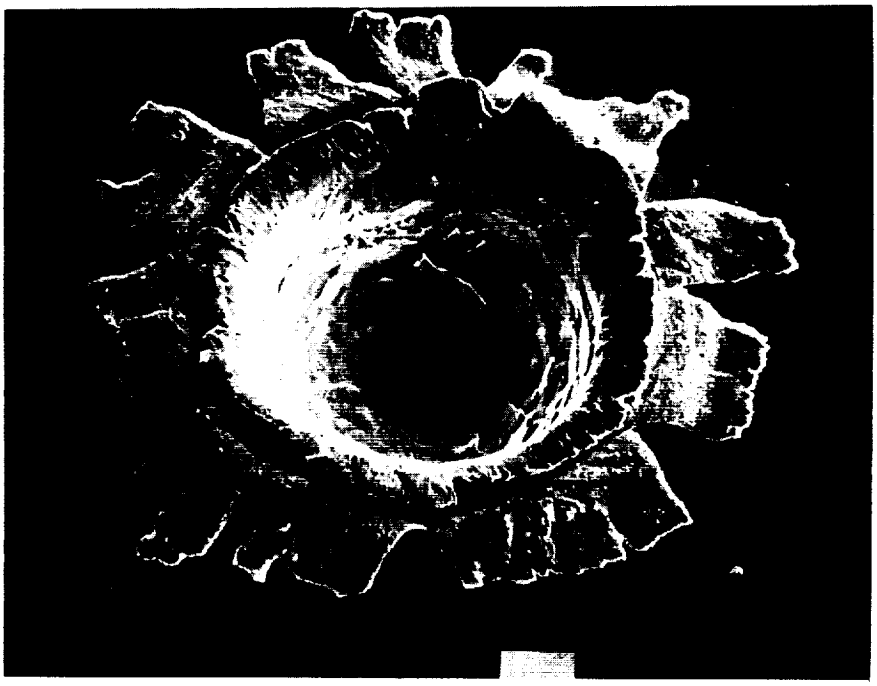
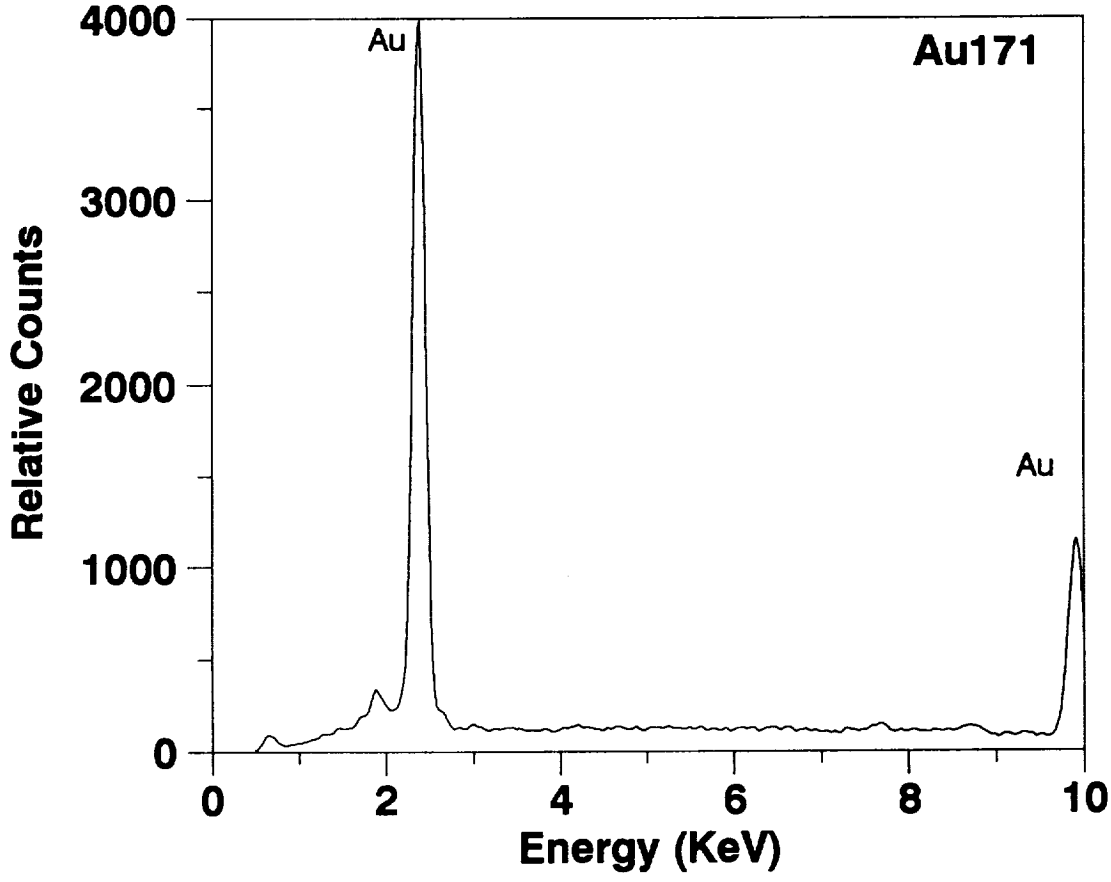
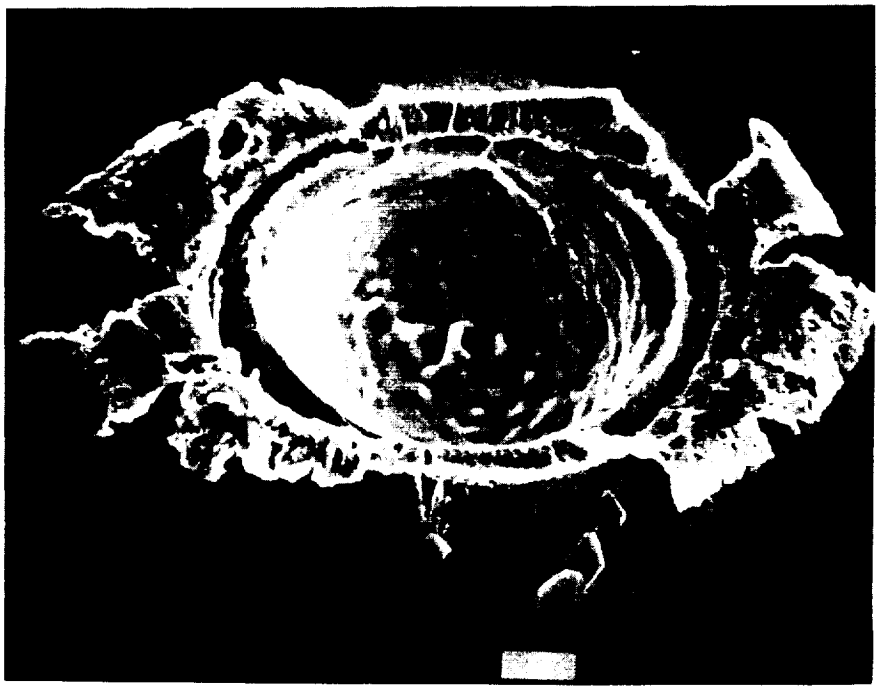


COMPONENT: EOOH
FEATURE: 171
CORE: LD-156

DIAMETER: 100 μm
ORIGIN: Unknown

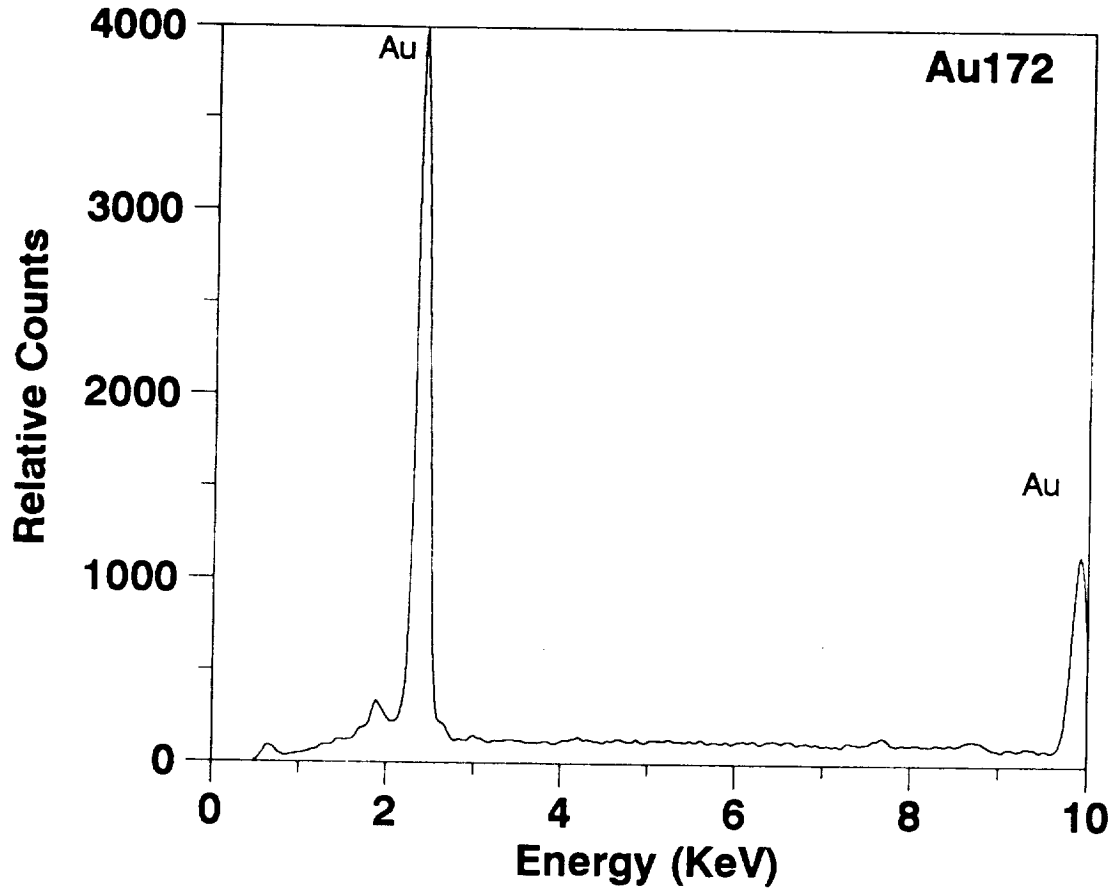


A03E00H



COMPONENT: EOOH
FEATURE: 172
CORE: LD-159

DIAMETER: 10 μm
ORIGIN: Unknown



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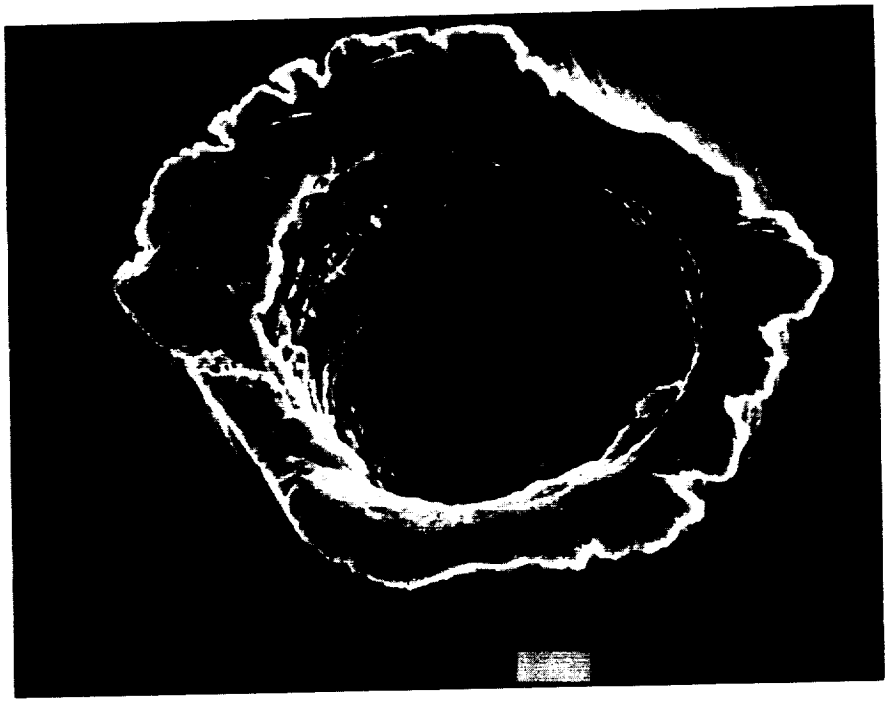
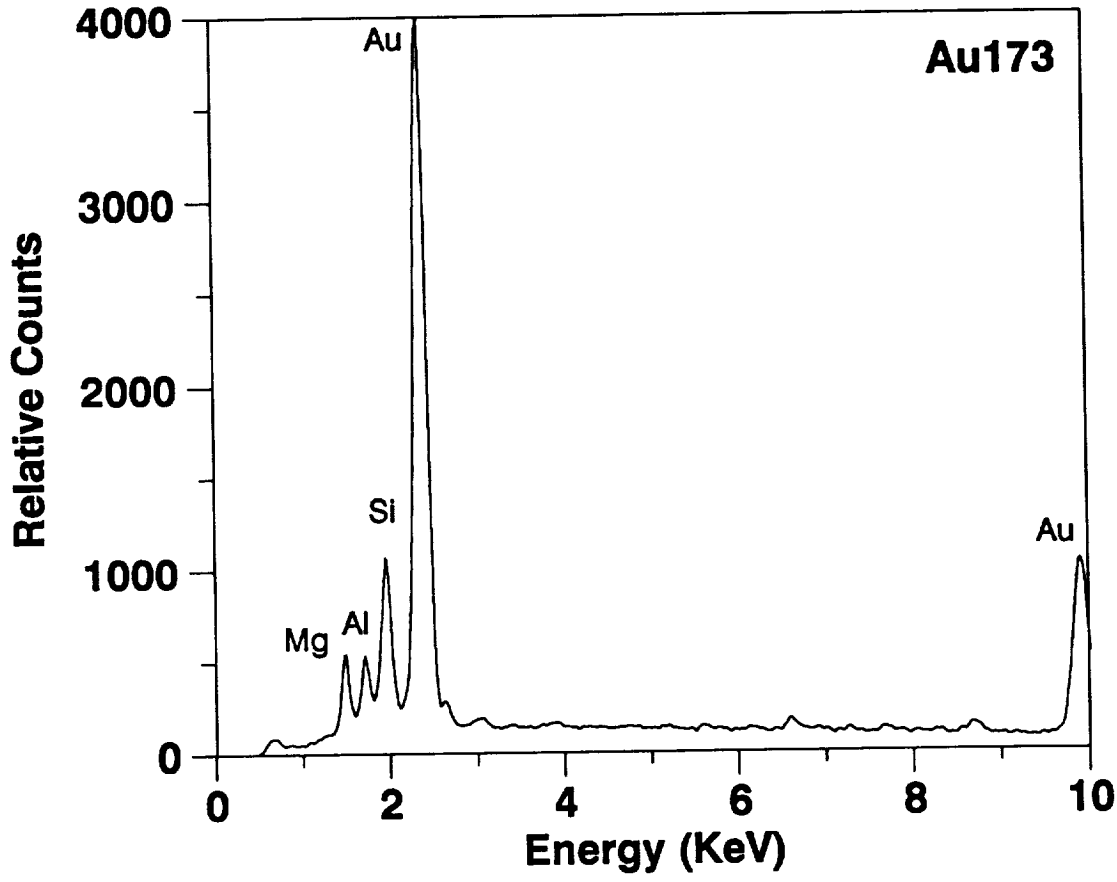


COMPONENT: EOOH
FEATURE: 173
CORE: LD-157

DIAMETER: 15 μm
ORIGIN: Natural



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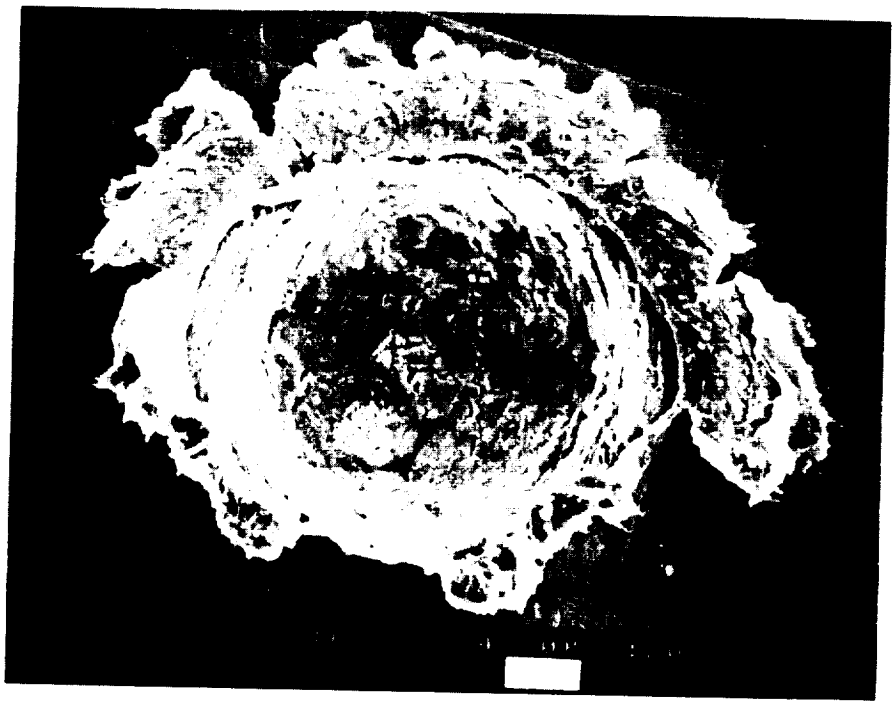
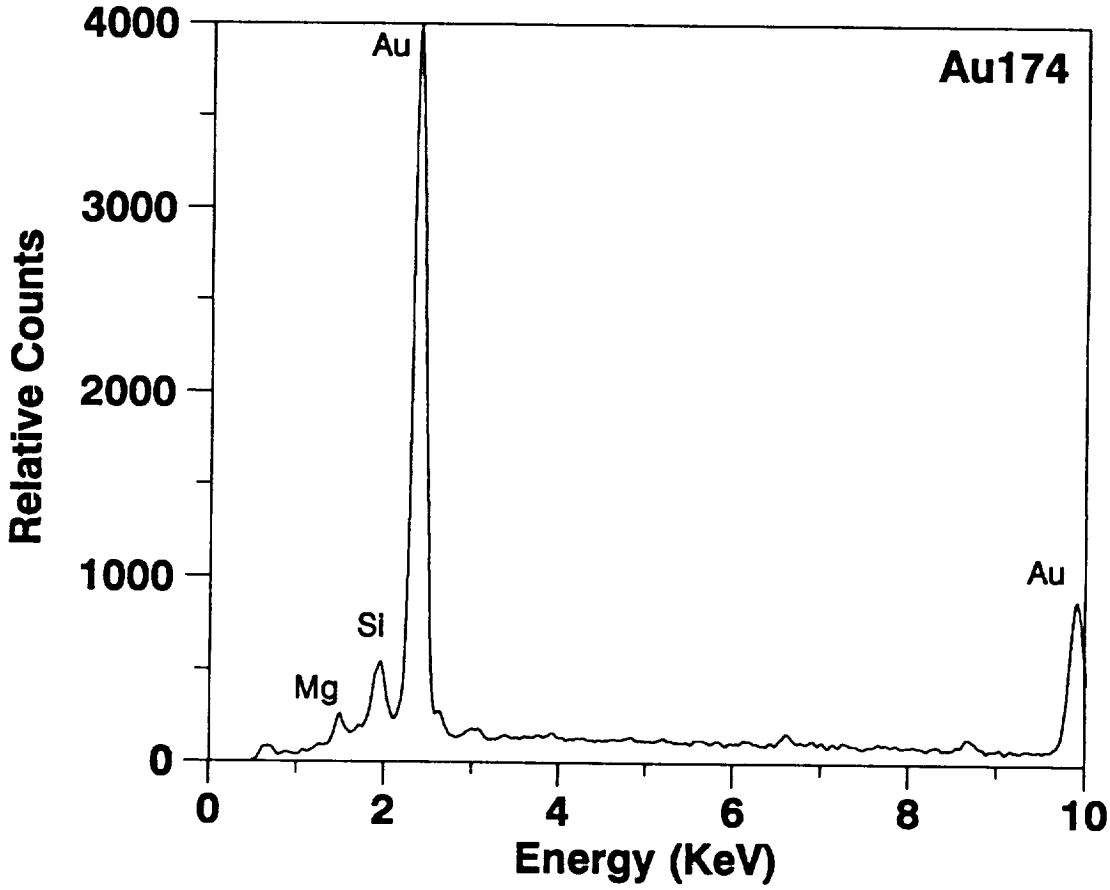


COMPONENT: EOOH
FEATURE: 174
CORE: LD-158

DIAMETER: 30 μm
ORIGIN: Natural



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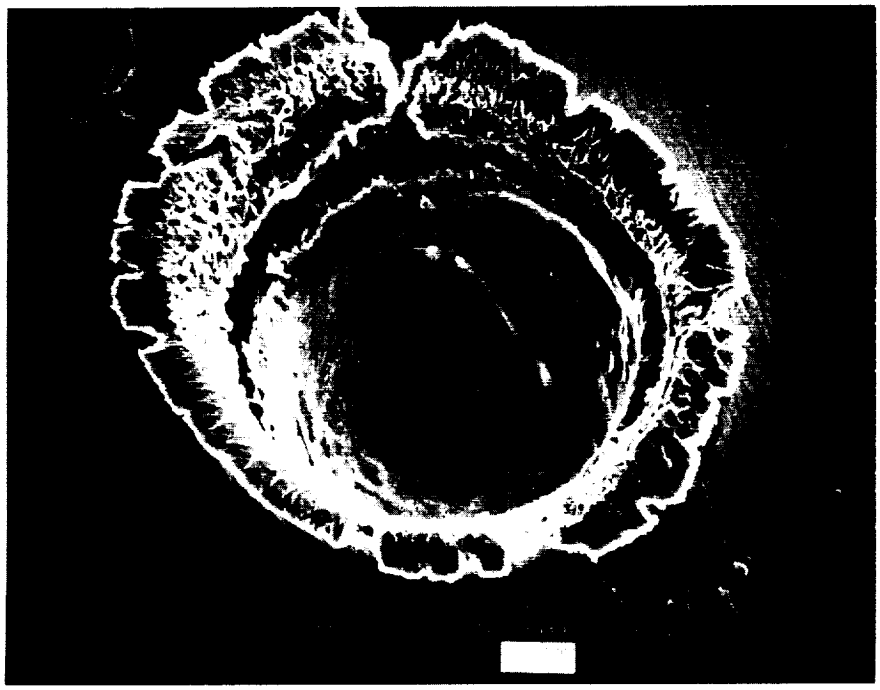
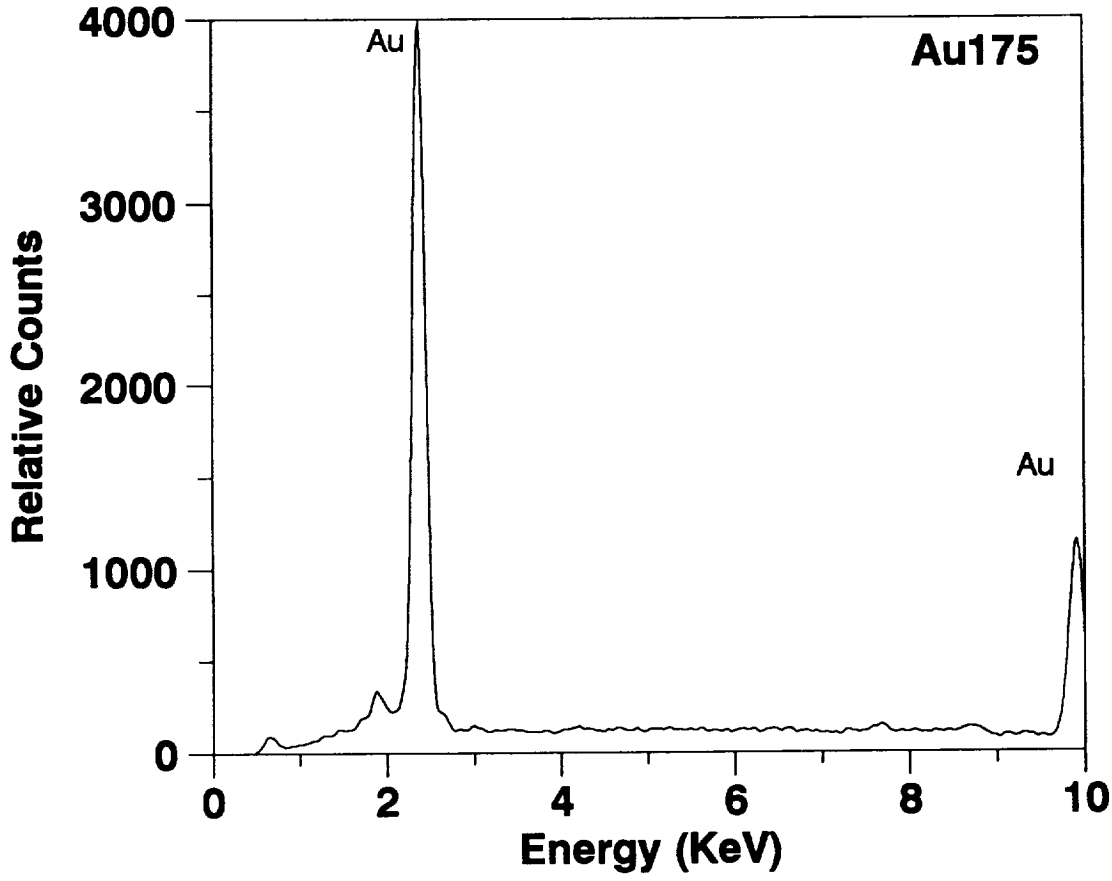


COMPONENT: EOOH
FEATURE: 175
CORE: LD-125

DIAMETER: 25 μm
ORIGIN: Unknown



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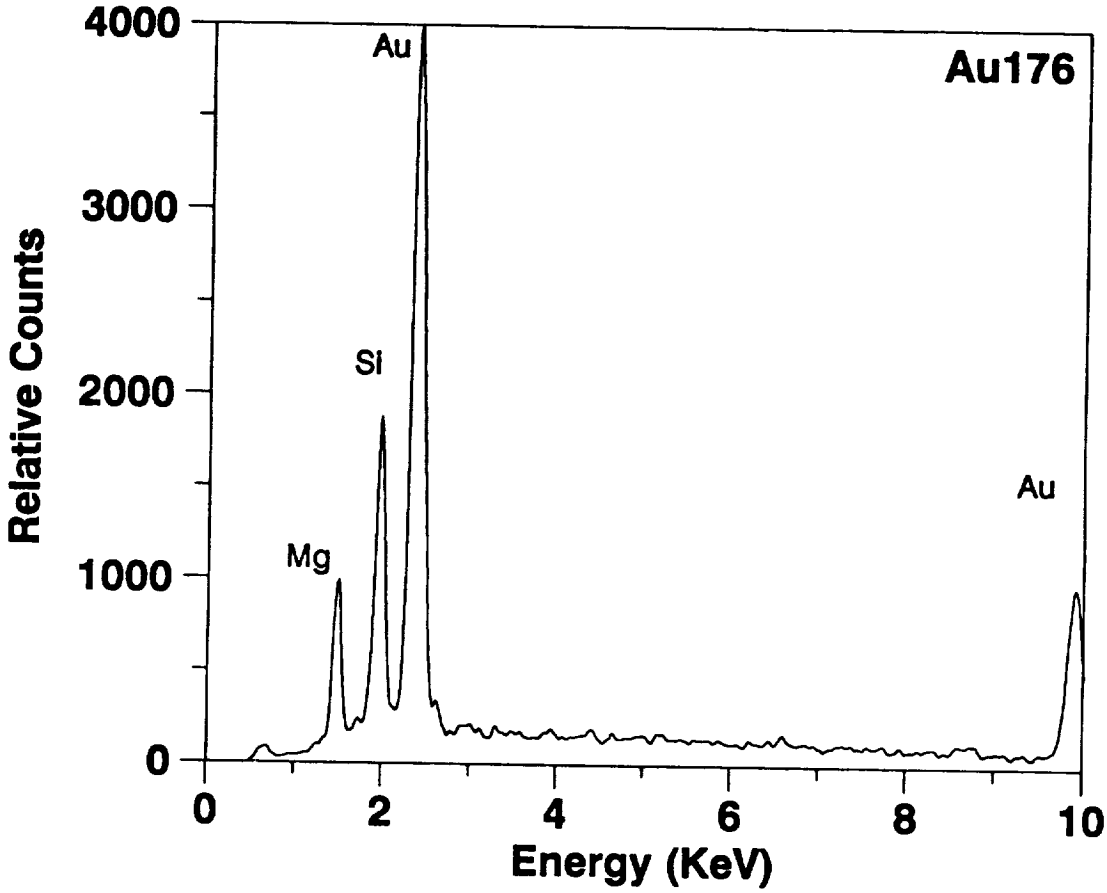
COMPONENT: EOOH
FEATURE: 176
CORE: LD-124

DIAMETER: 245 μm
ORIGIN: Natural



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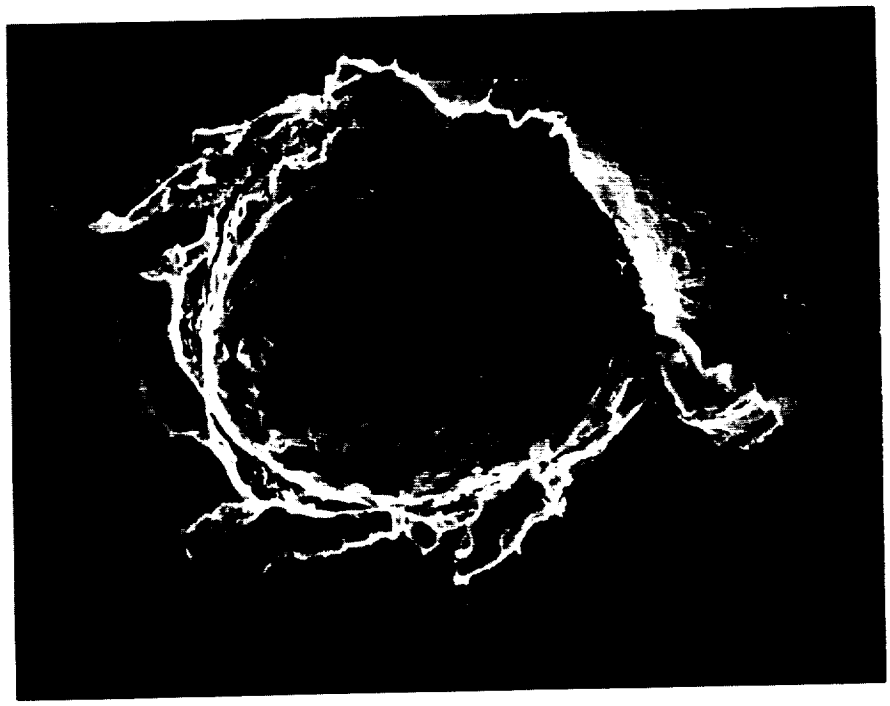
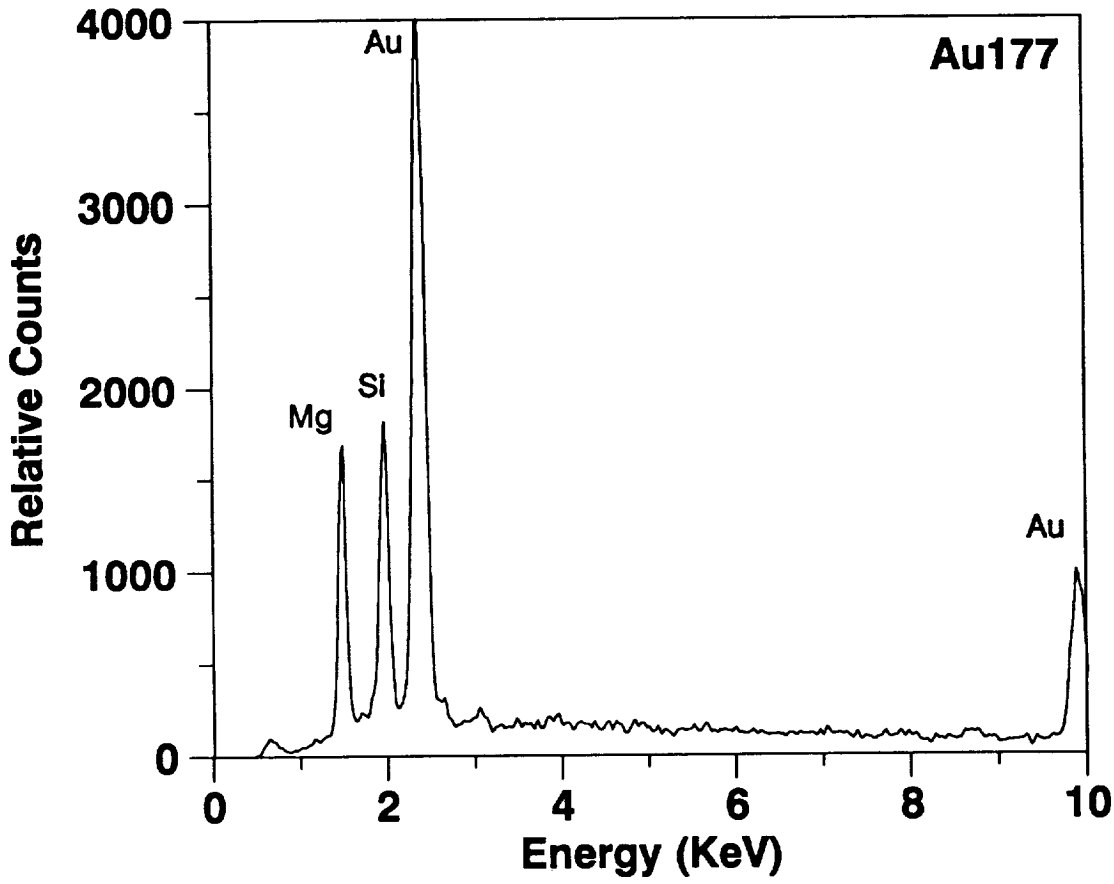


COMPONENT: EOOH
FEATURE: 177
CORE: LD-121

DIAMETER: 30 μm
ORIGIN: Natural



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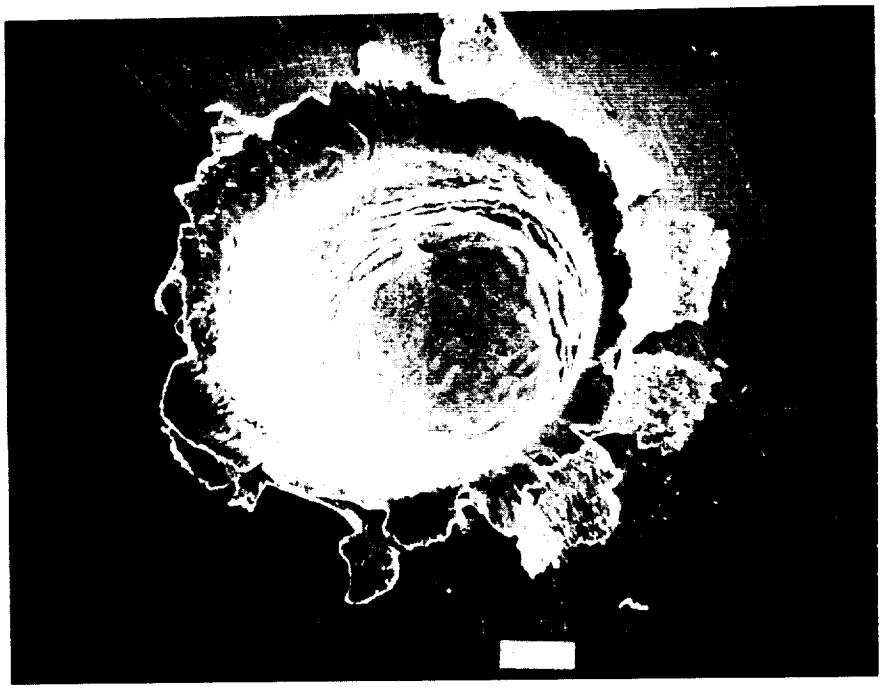
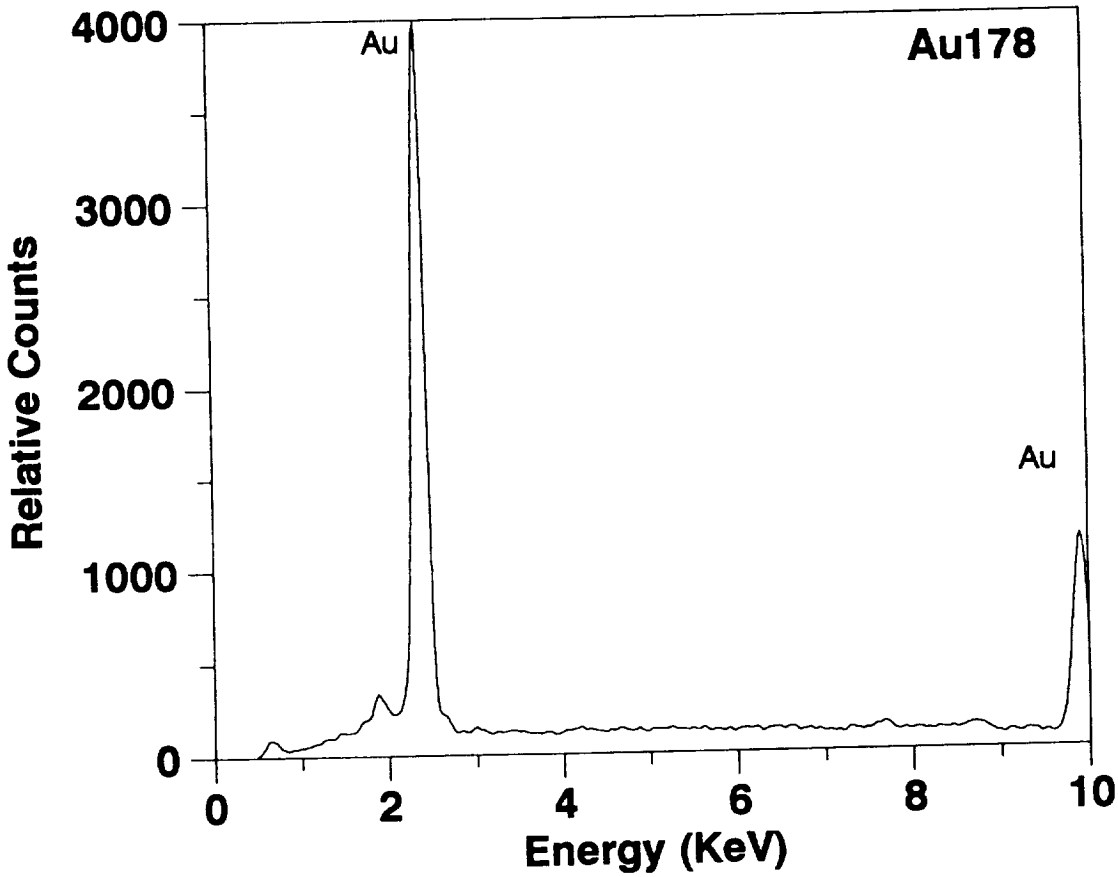


COMPONENT: EOOH
FEATURE: 178
CORE: LD-126

DIAMETER: 55 μm
ORIGIN: Unknown



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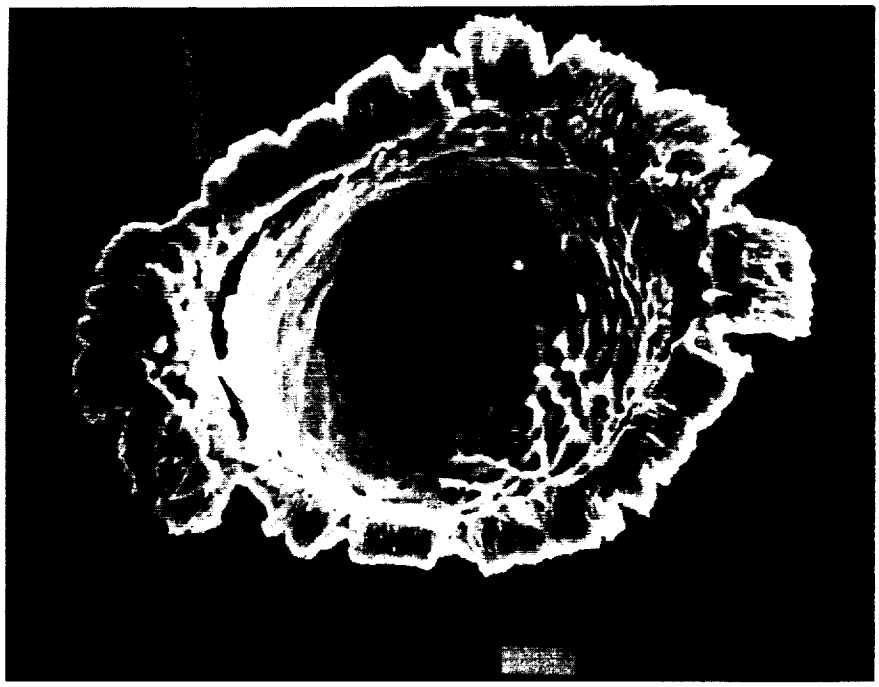
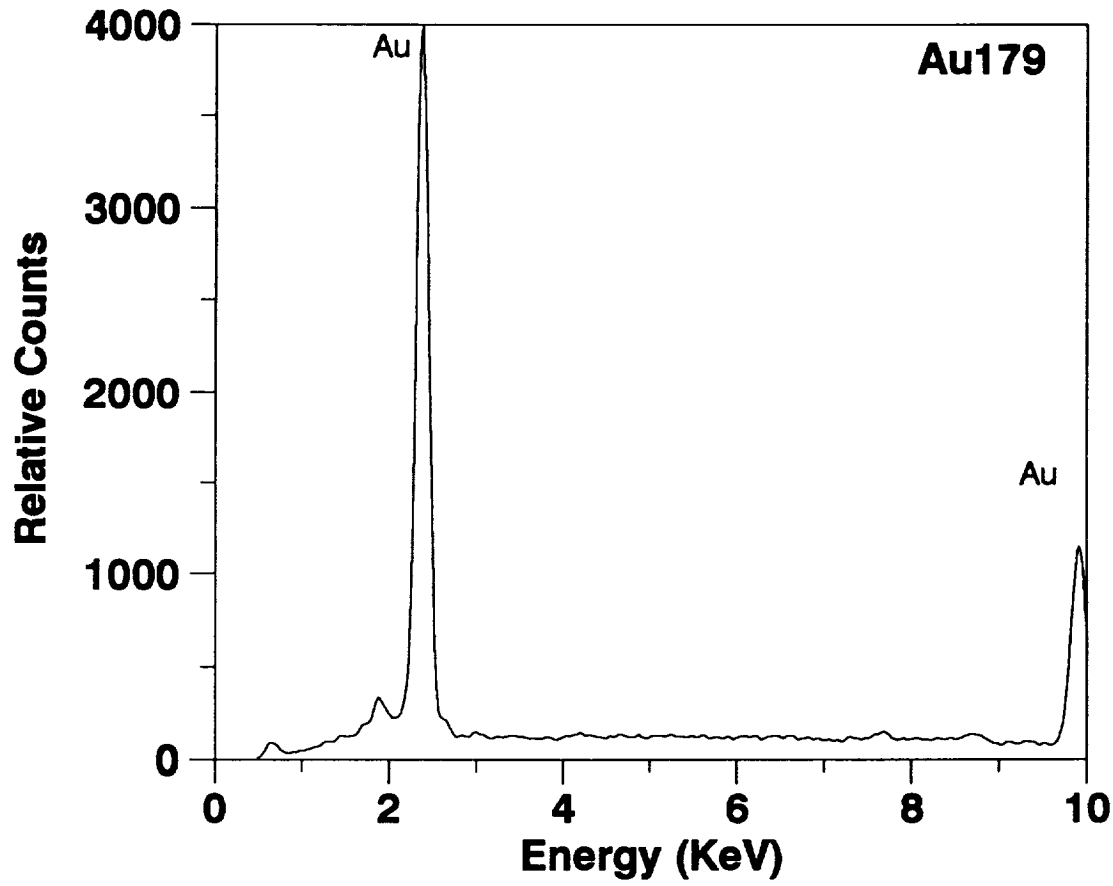


COMPONENT: EOOH
FEATURE: 179
CORE: LD-122

DIAMETER: 15 μm
ORIGIN: Unknown



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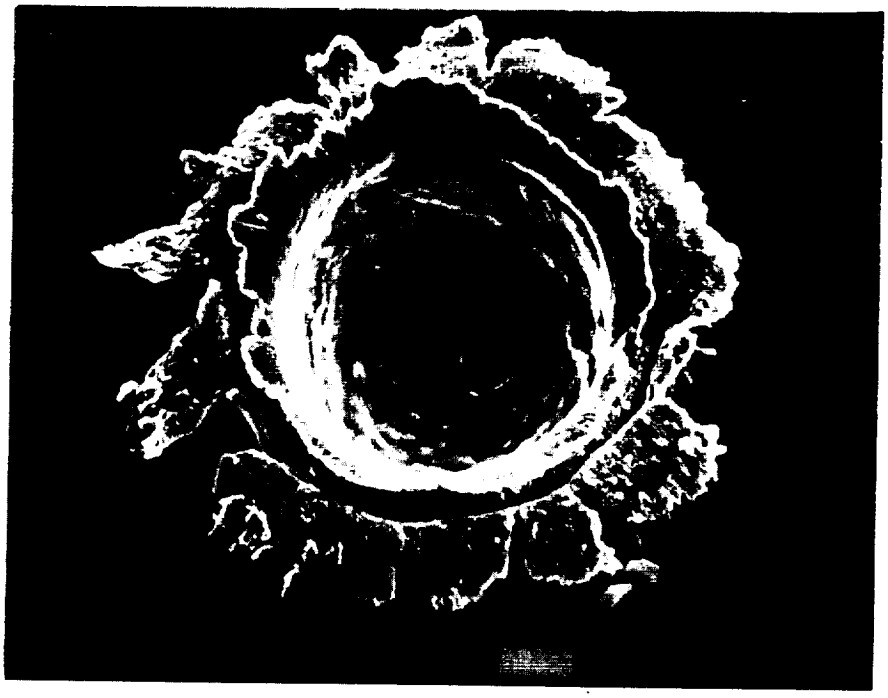
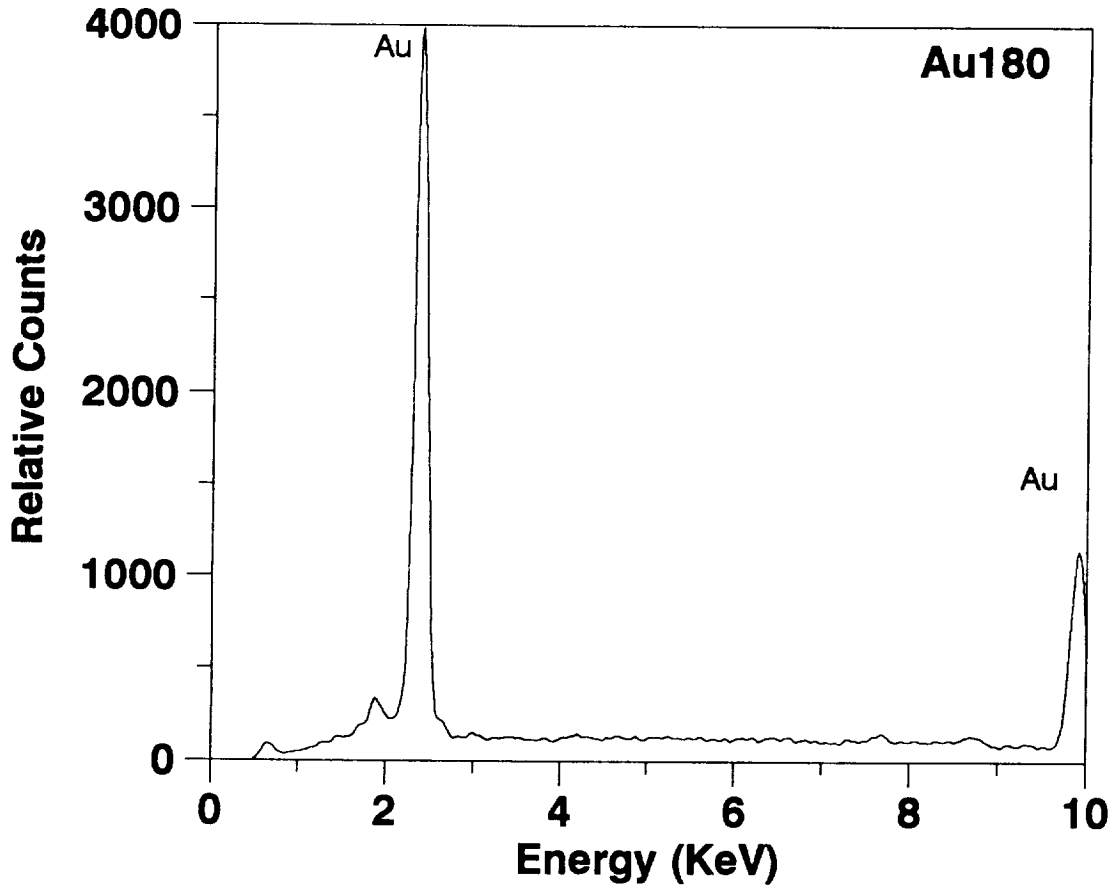


COMPONENT: EOOH
FEATURE: 180
CORE: LD-127

DIAMETER: 35 μm
ORIGIN: Unknown



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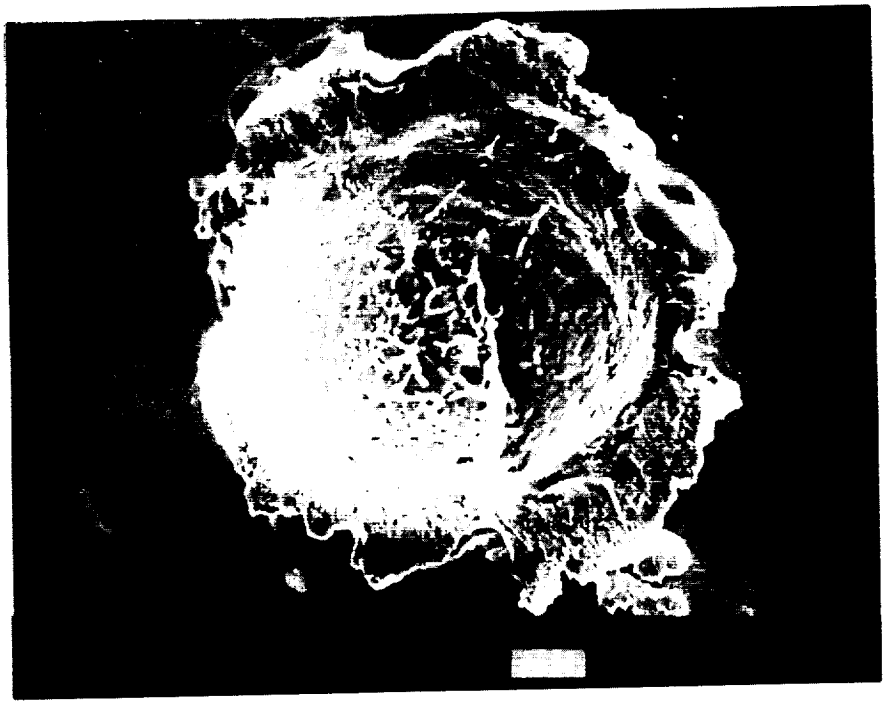
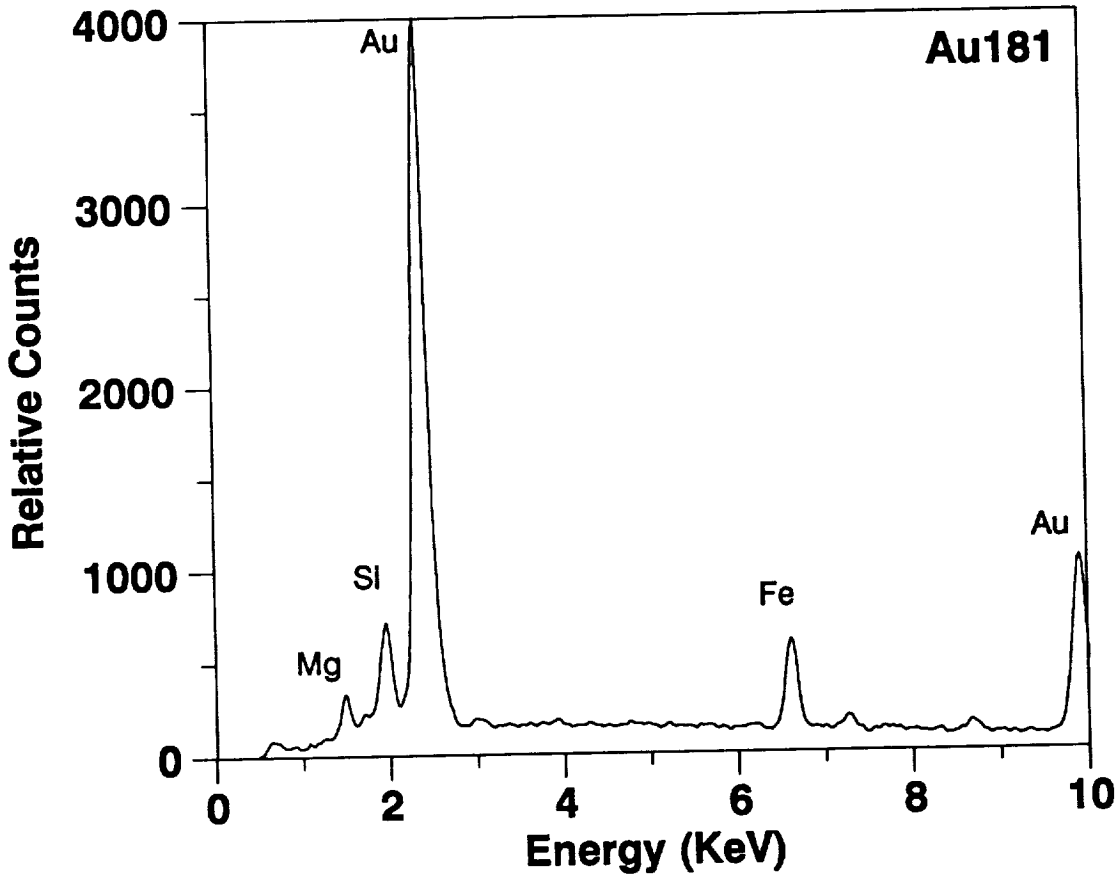


COMPONENT: EOOH
FEATURE: 181
CORE: LD-123

DIAMETER: 65 μm
ORIGIN: Natural



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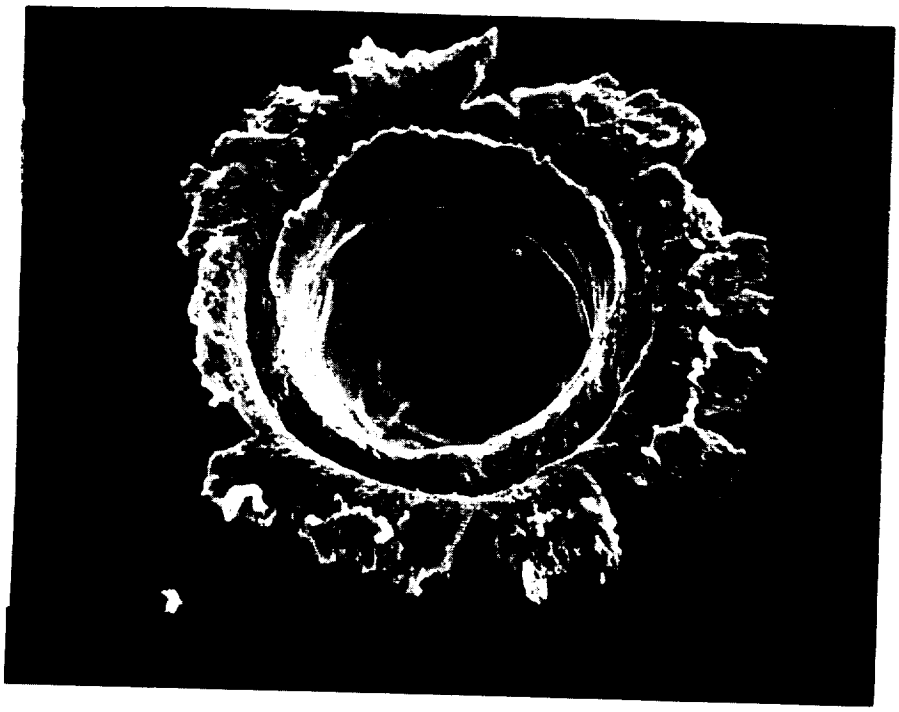
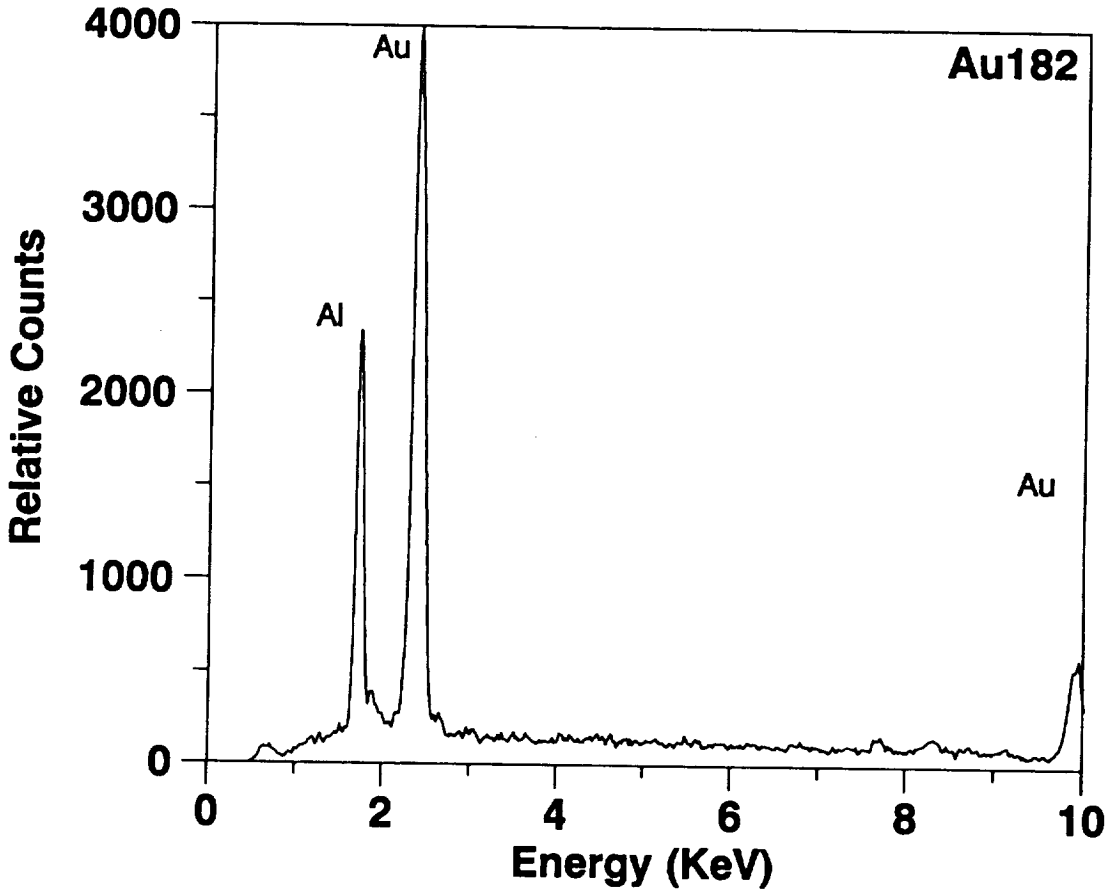


COMPONENT: EOOH
FEATURE: 182
CORE: LD-128

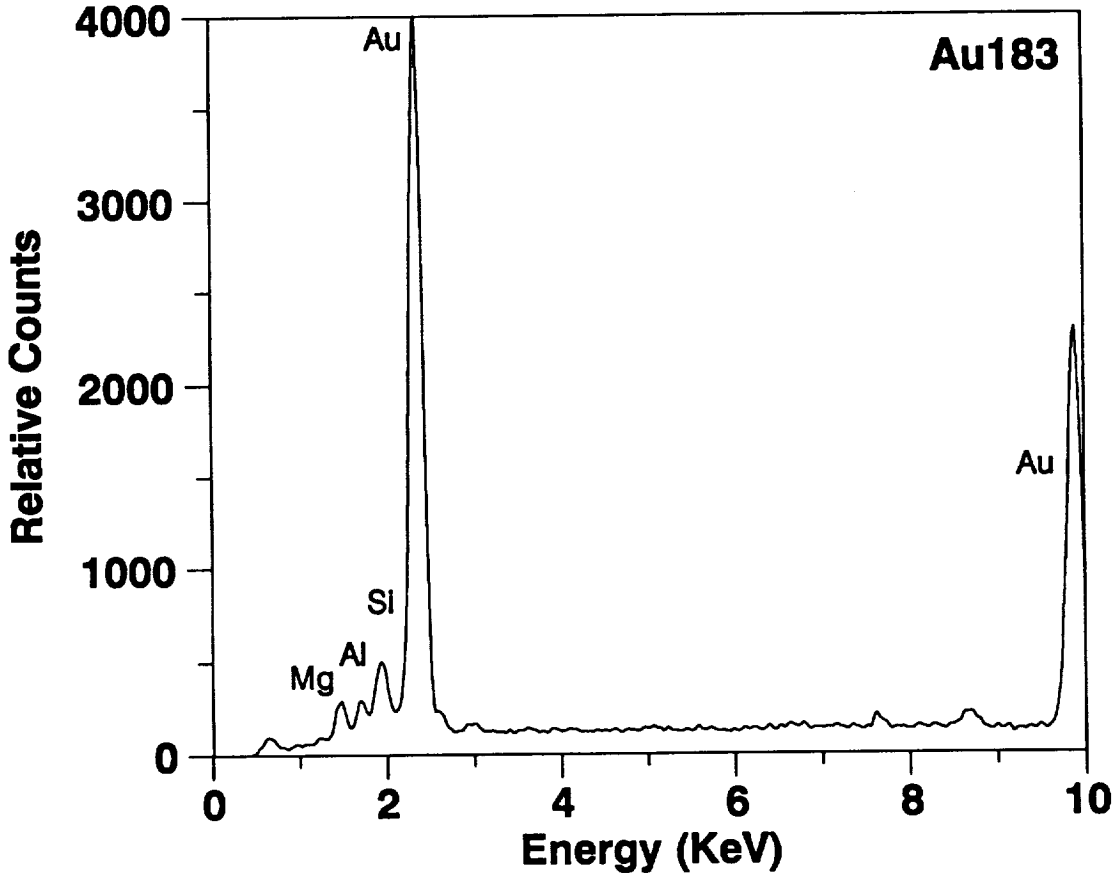
DIAMETER: 20 μm
ORIGIN: Man-made



A03E00H

COMPONENT: EOOH
FEATURE: 183
CORE: LD-129

DIAMETER: 35 μm
ORIGIN: Natural



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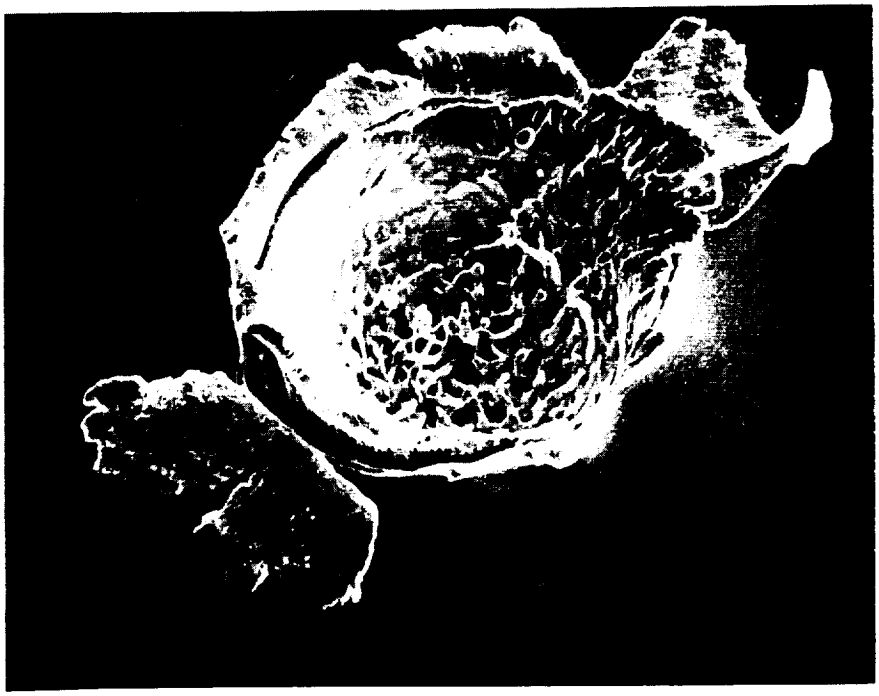
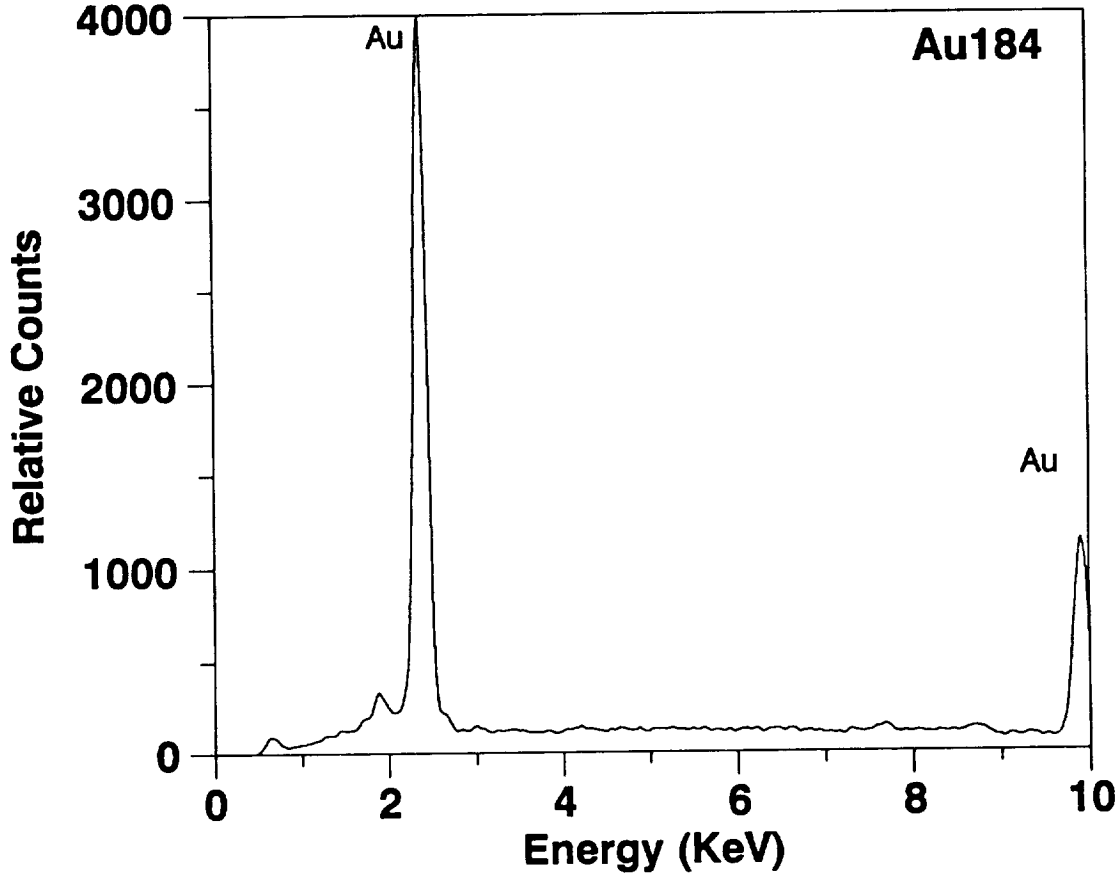


COMPONENT: EOOH
FEATURE: 184
CORE: LD-129

DIAMETER: 60 μm
ORIGIN: Unknown



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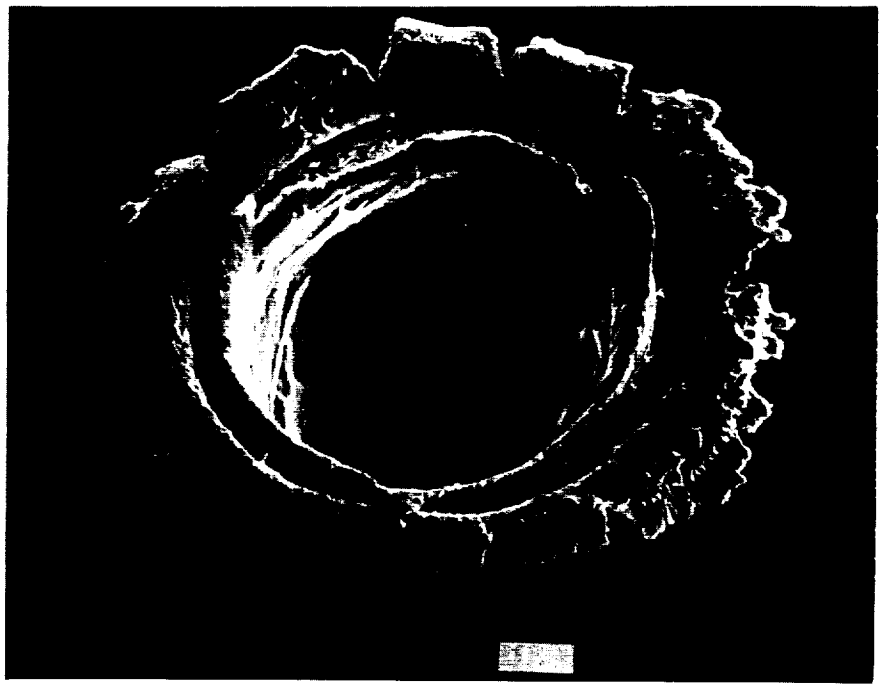
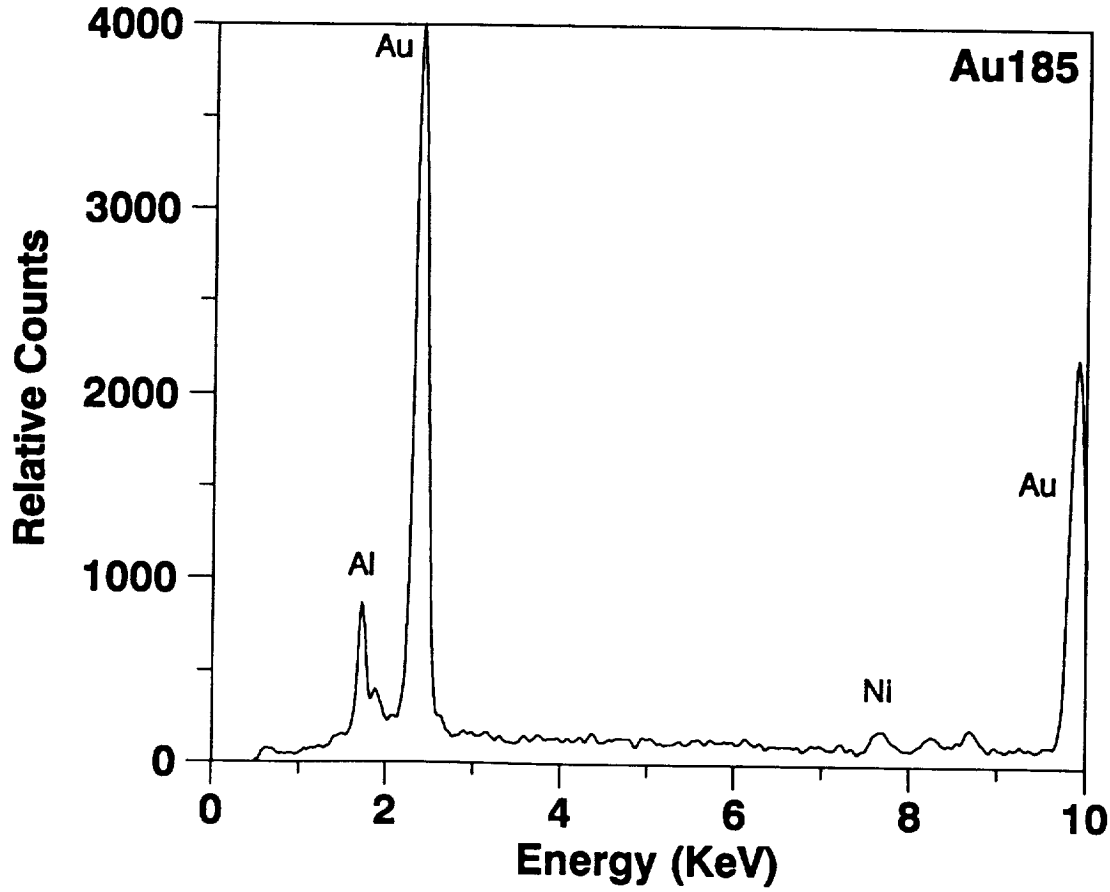


COMPONENT: EOOH
FEATURE: 185
CORE: LD-130

DIAMETER: 45 μm
ORIGIN: Man-made



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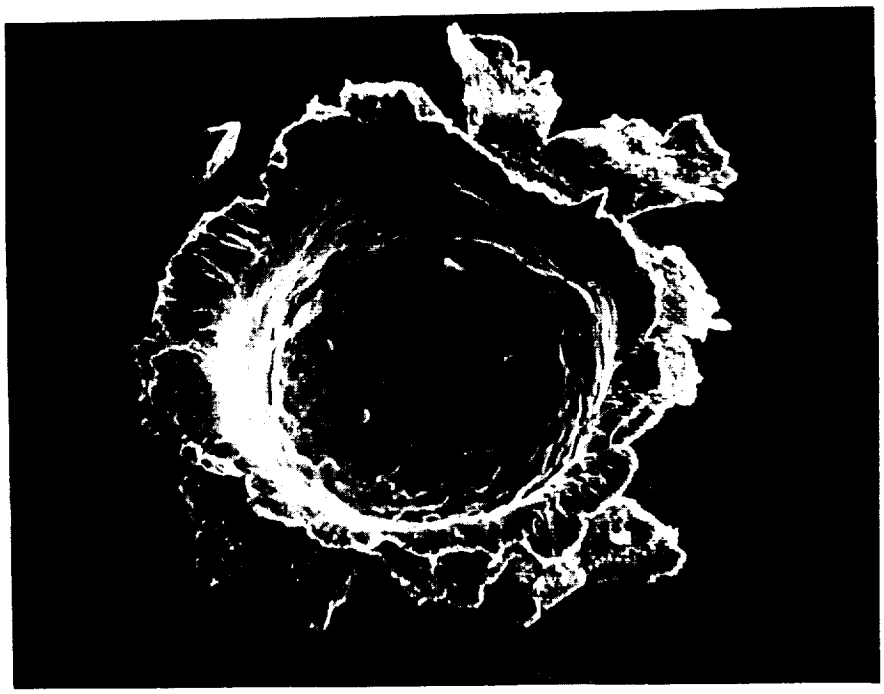
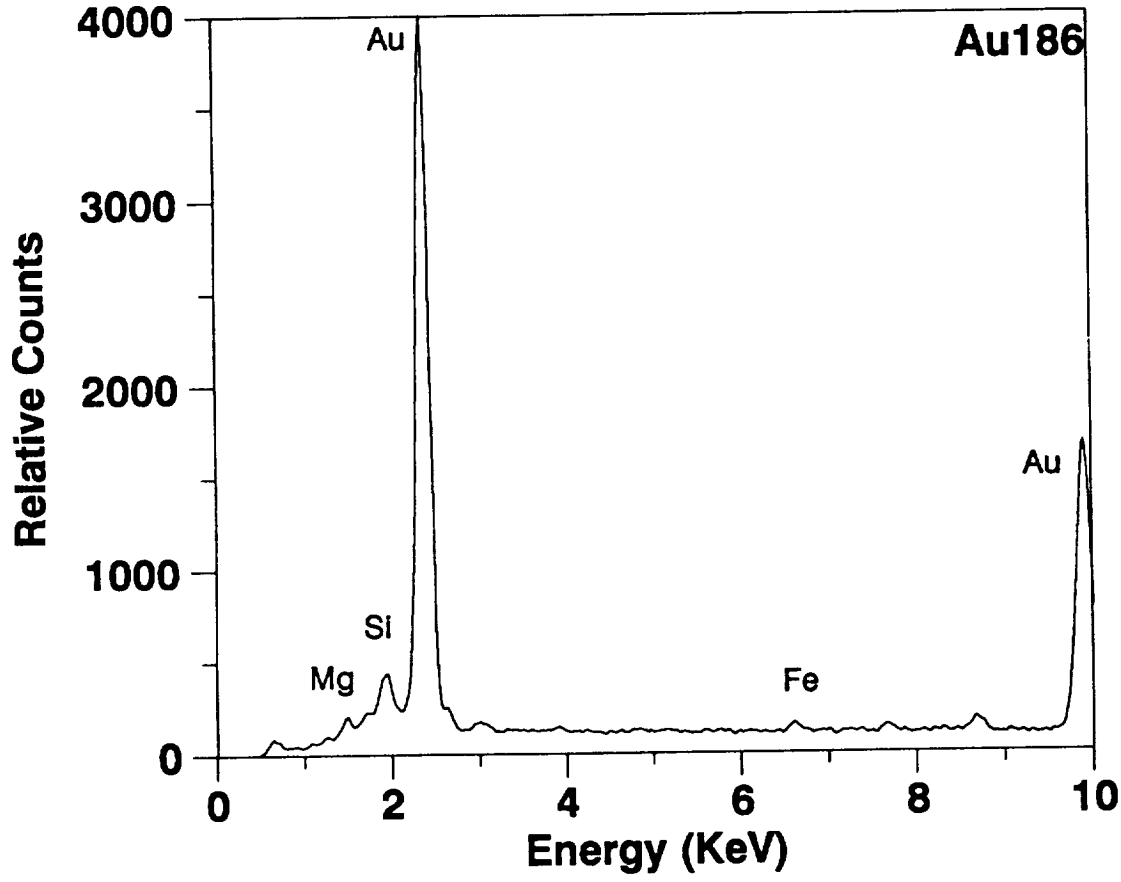


COMPONENT: EOOH
FEATURE: 186
CORE: LD-131

DIAMETER: 40 μm
ORIGIN: Natural



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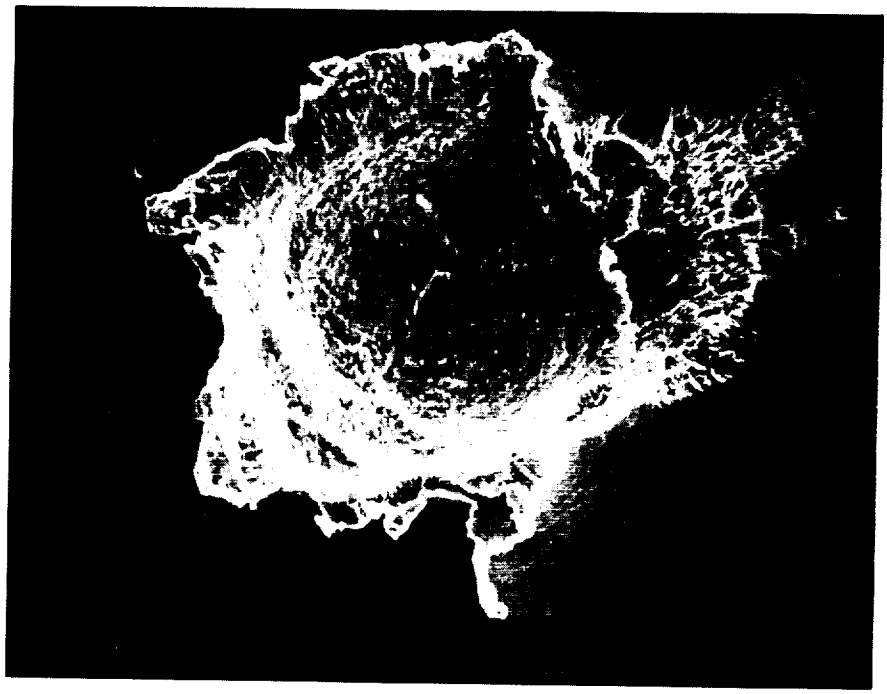
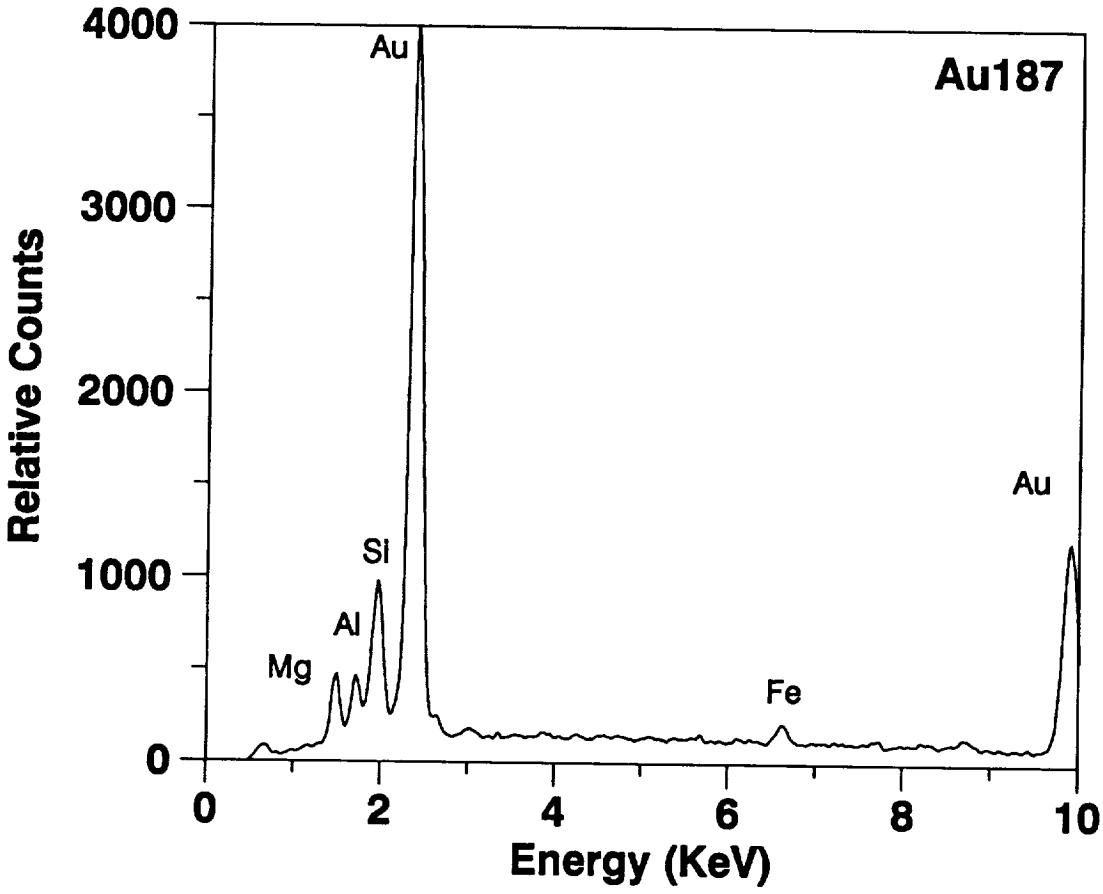


COMPONENT: EOOH
FEATURE: 187
CORE: LD-132

DIAMETER: 60 μm
ORIGIN: Natural



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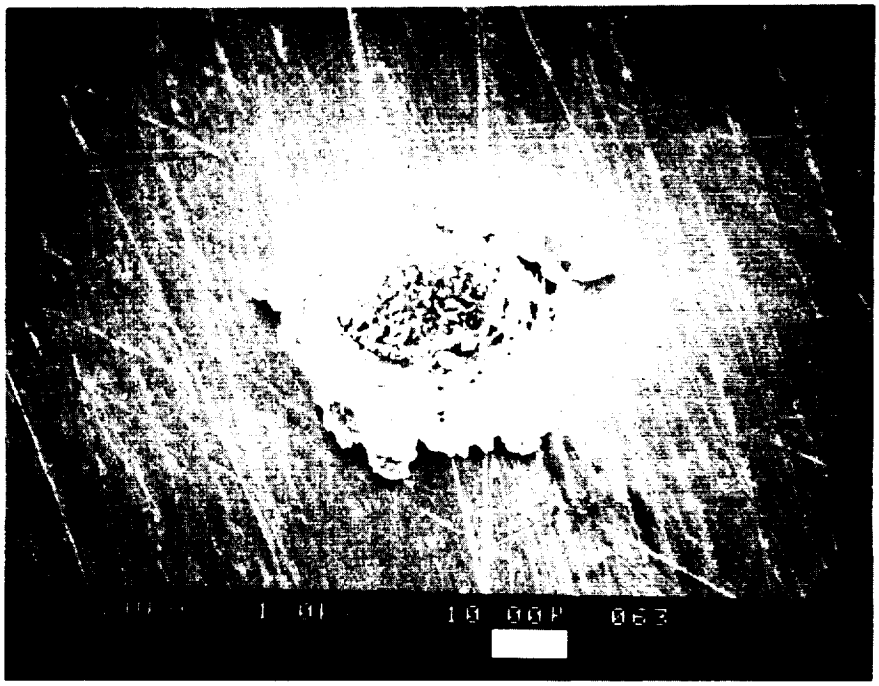
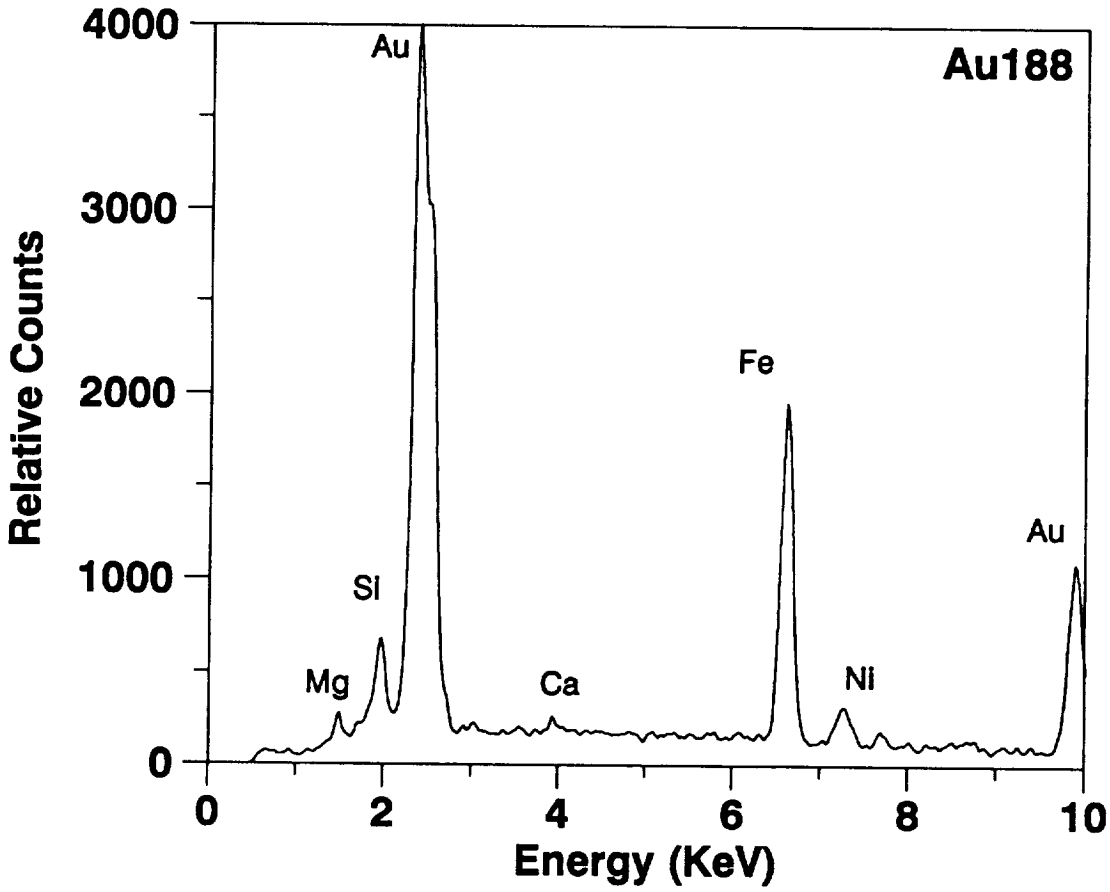


COMPONENT: EOOH
FEATURE: 188
CORE: LD-133

DIAMETER: 25 μm
ORIGIN: Natural



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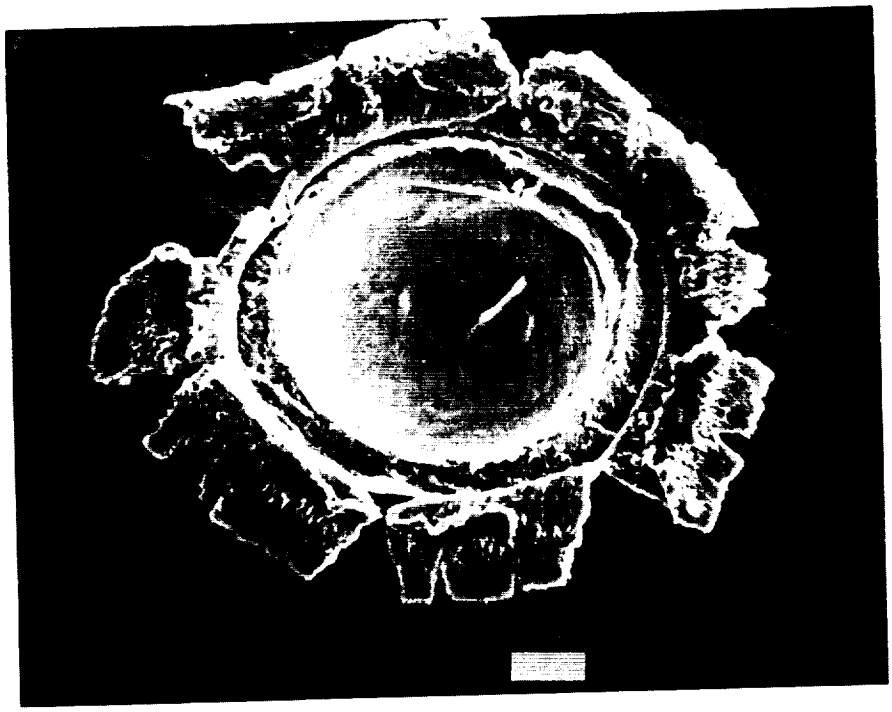
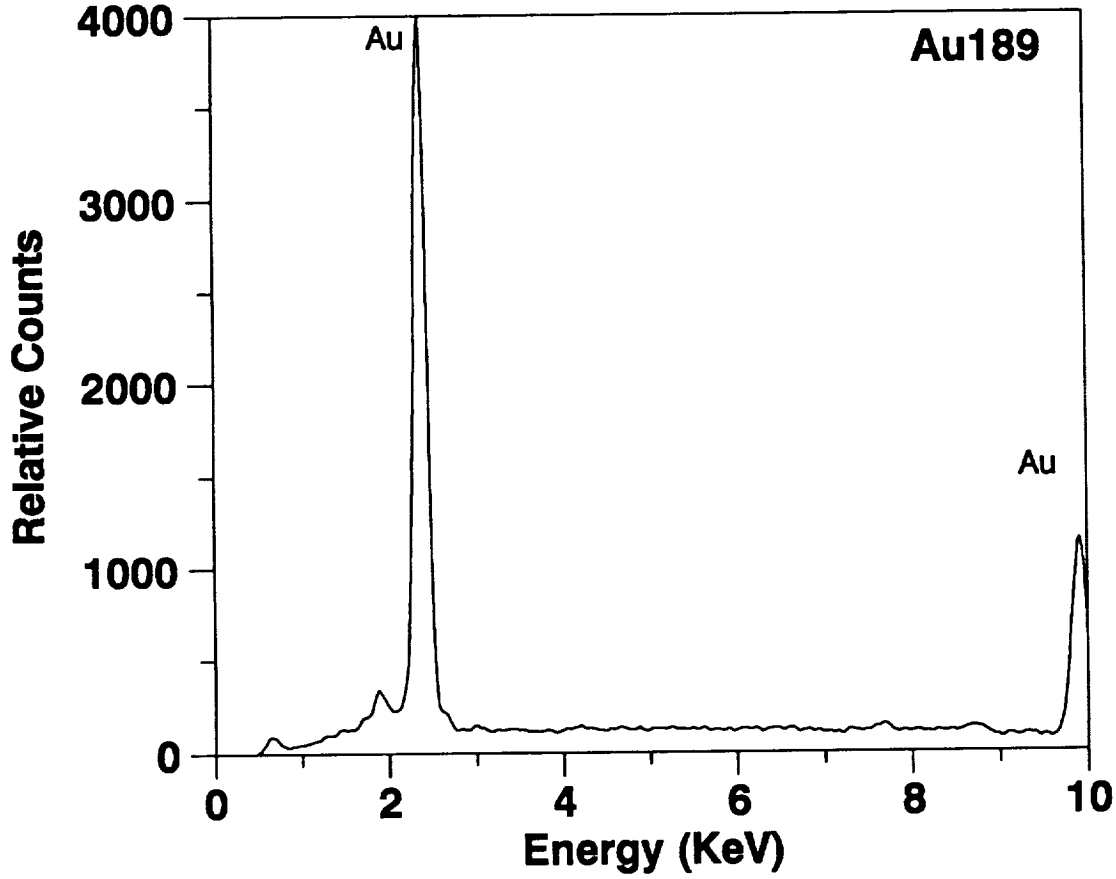


COMPONENT: EOOH
FEATURE: 189
CORE: LD-136

DIAMETER: 25 μm
ORIGIN: Unknown



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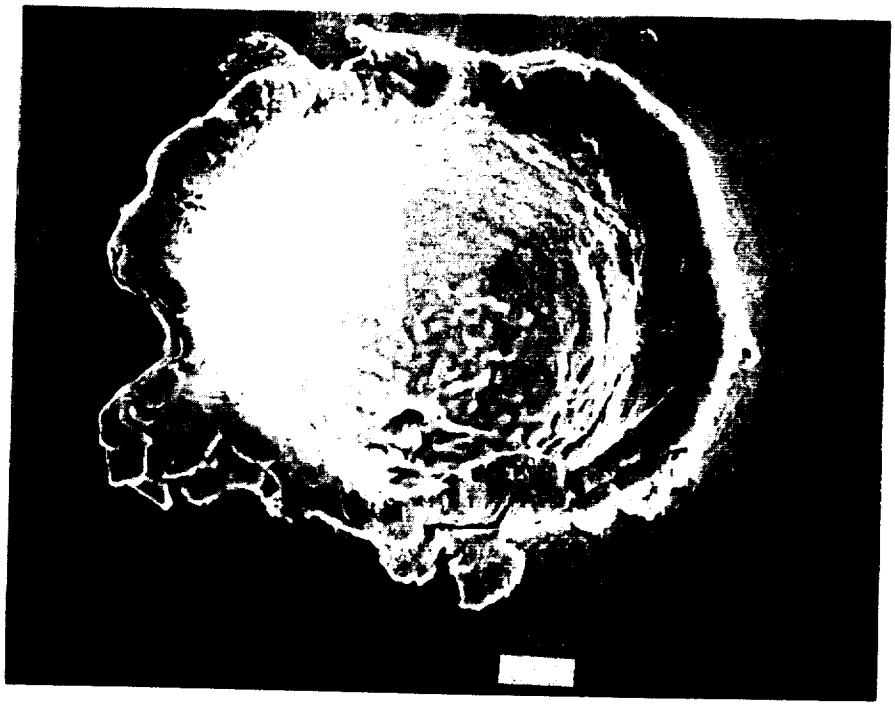
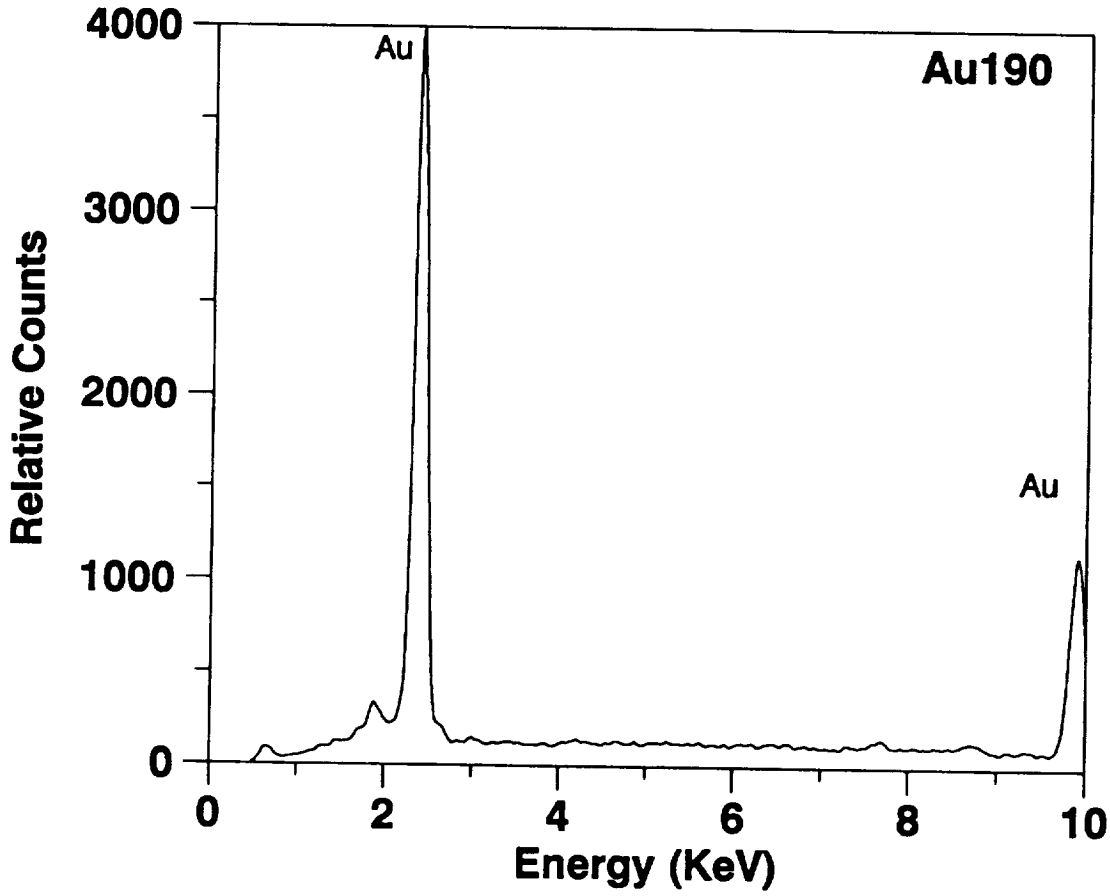


COMPONENT: EOOH
FEATURE: 190
CORE: LD-134

DIAMETER: 40 μm
ORIGIN: Unknown



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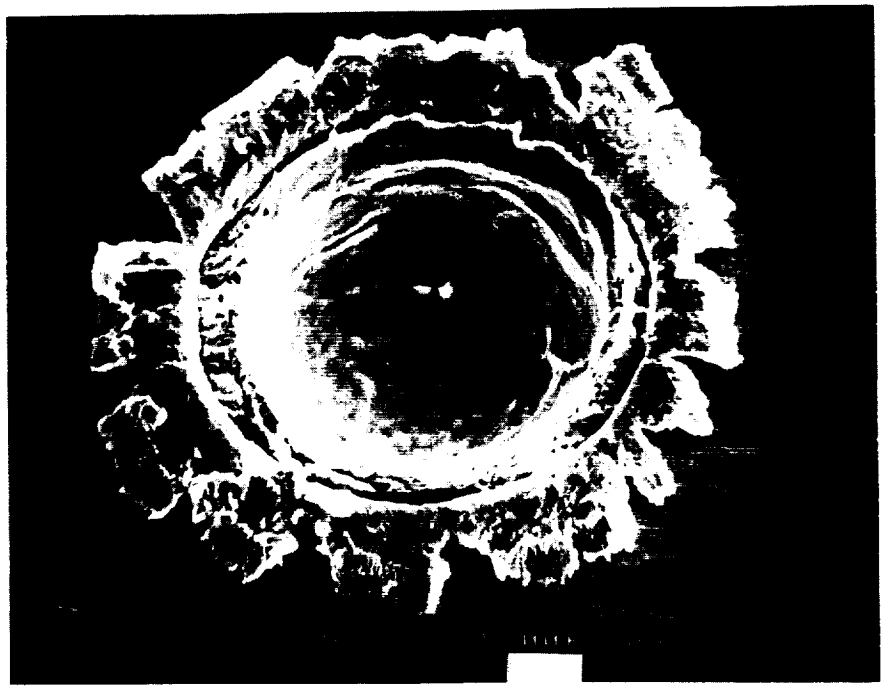
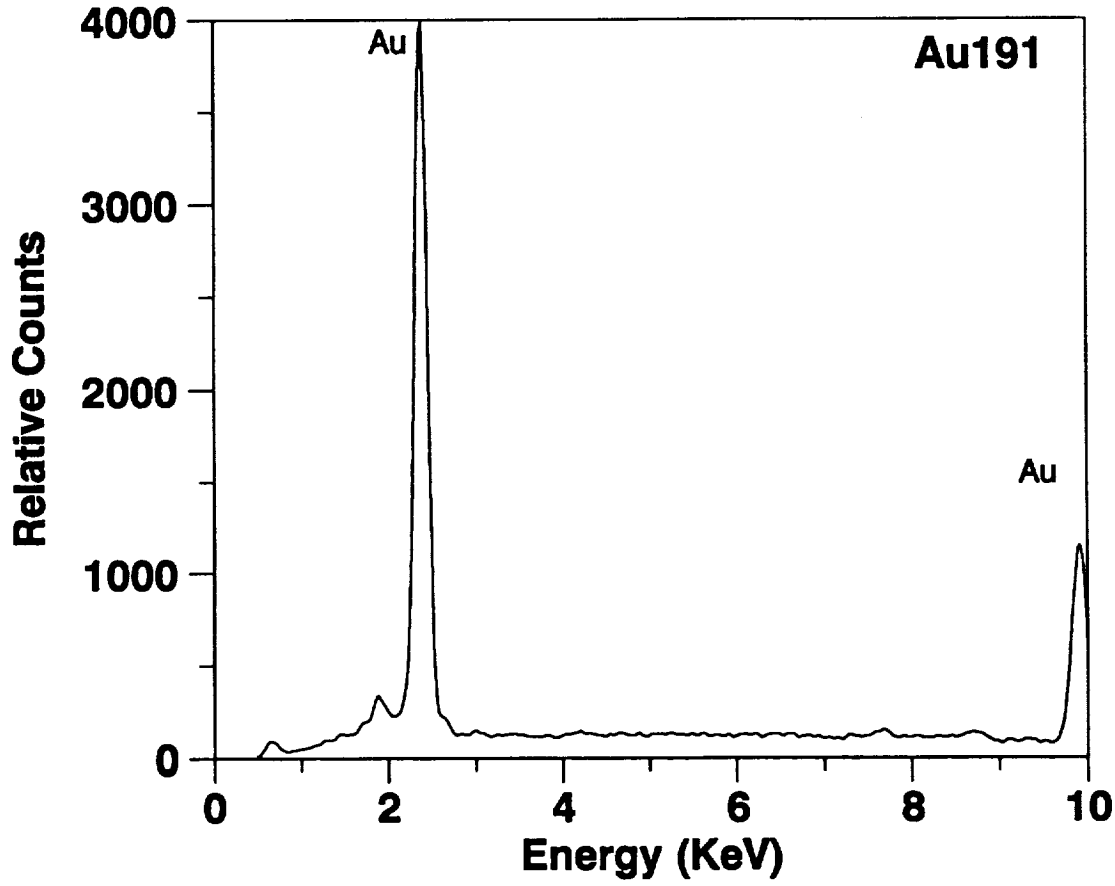


COMPONENT: EOOH
FEATURE: 191
CORE: LD-135

DIAMETER: 25 μm
ORIGIN: Unknown



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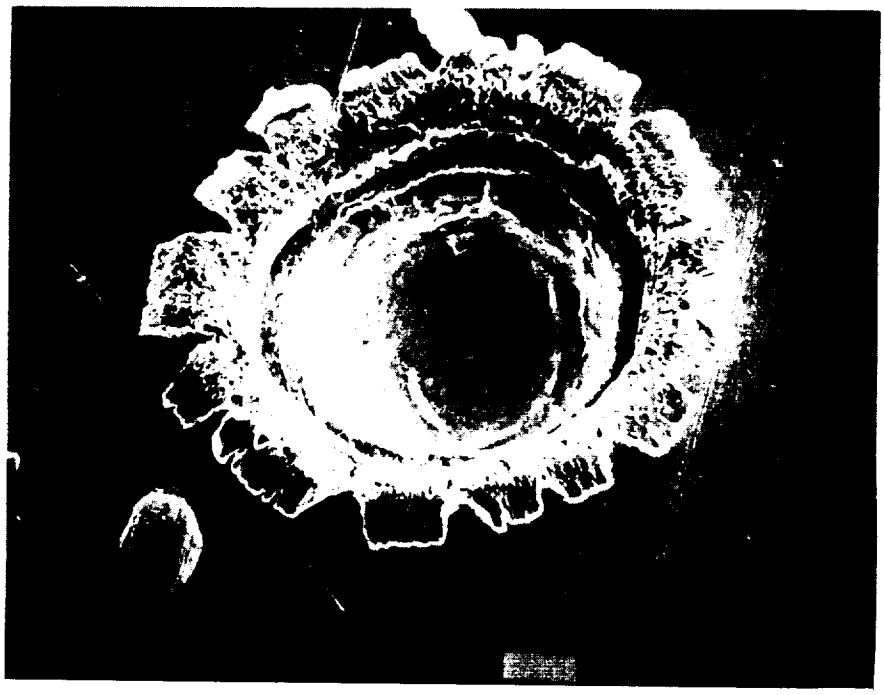
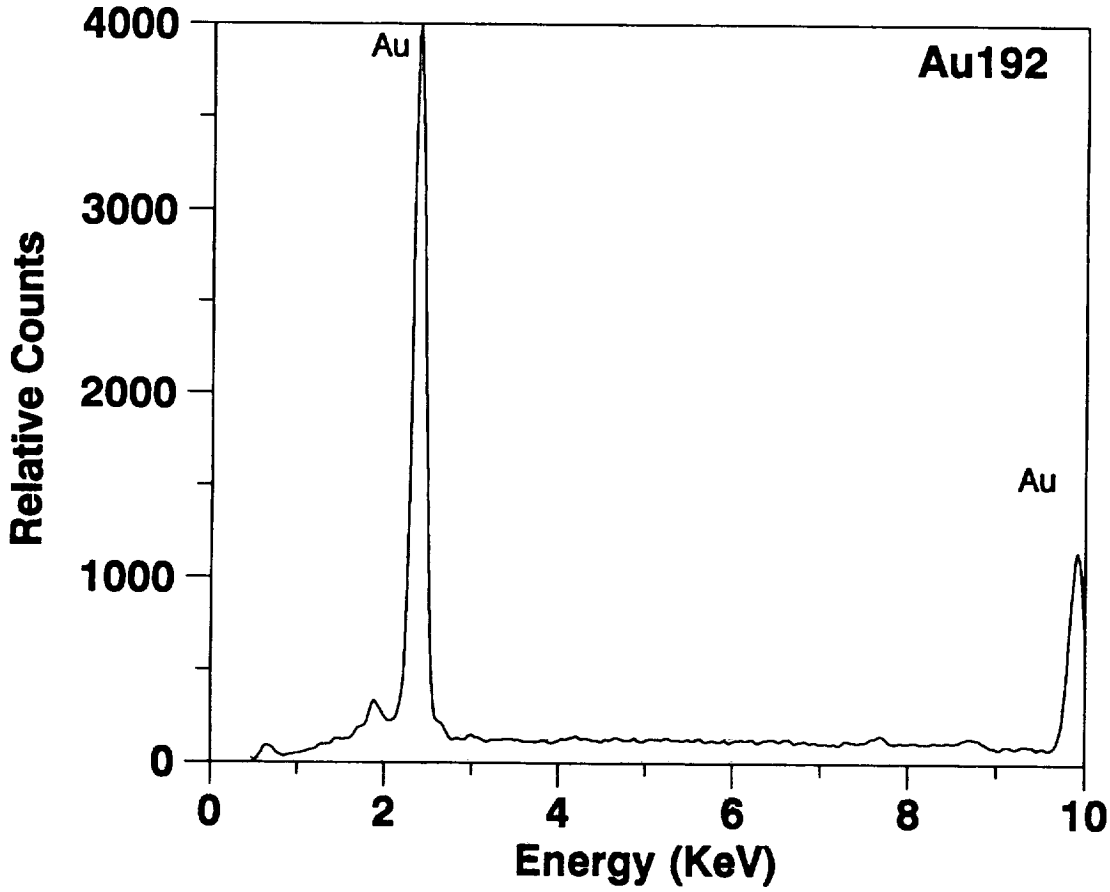


COMPONENT: EOOH
FEATURE: 192
CORE: LD-152

DIAMETER: 55 μm
ORIGIN: Unknown



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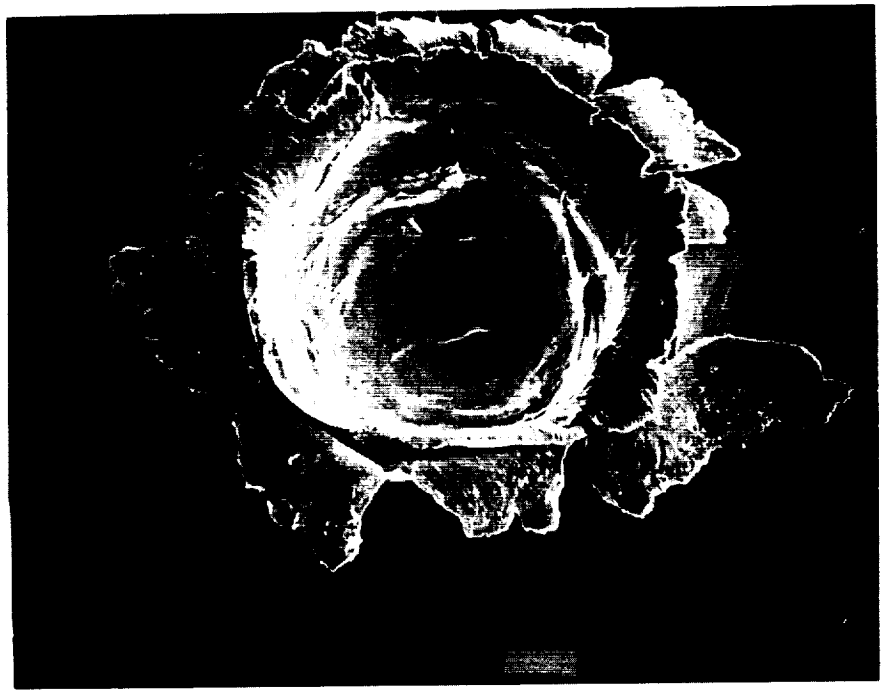
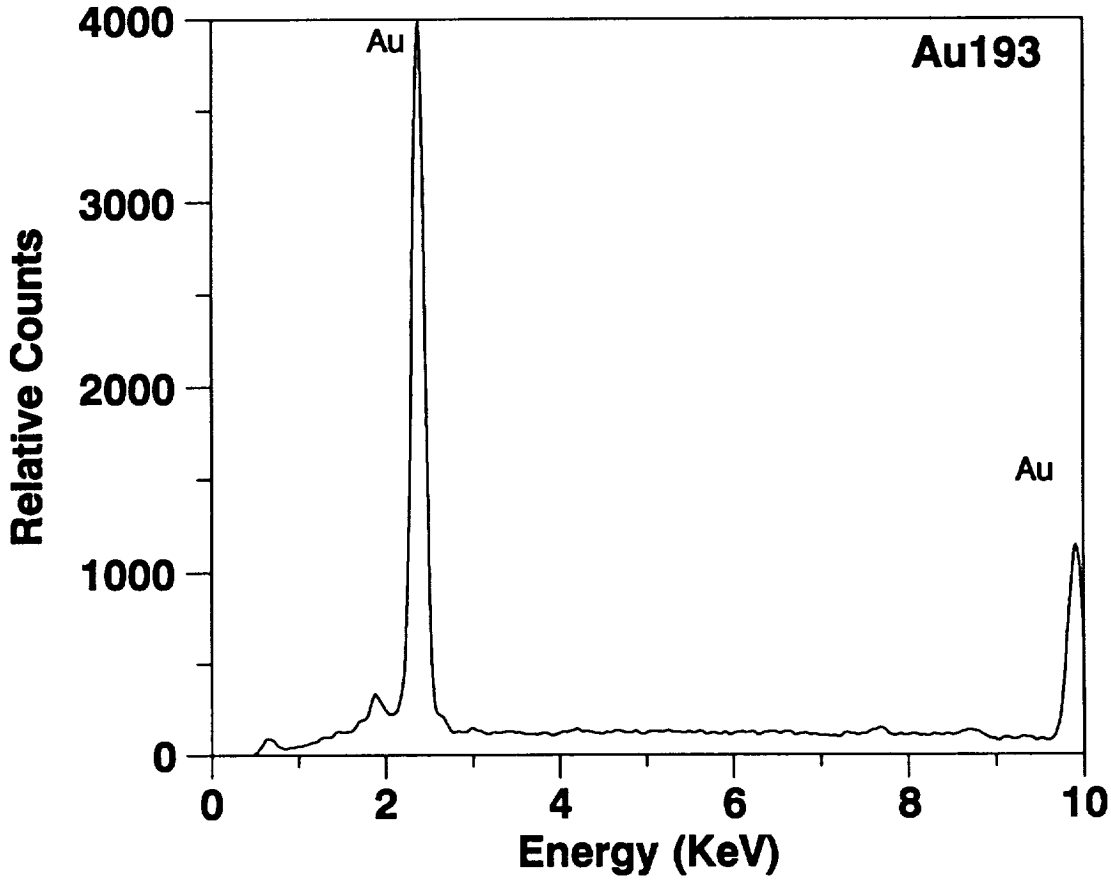


COMPONENT: EOOH
FEATURE: 193
CORE: LD-155

DIAMETER: 100 μm
ORIGIN: Unknown



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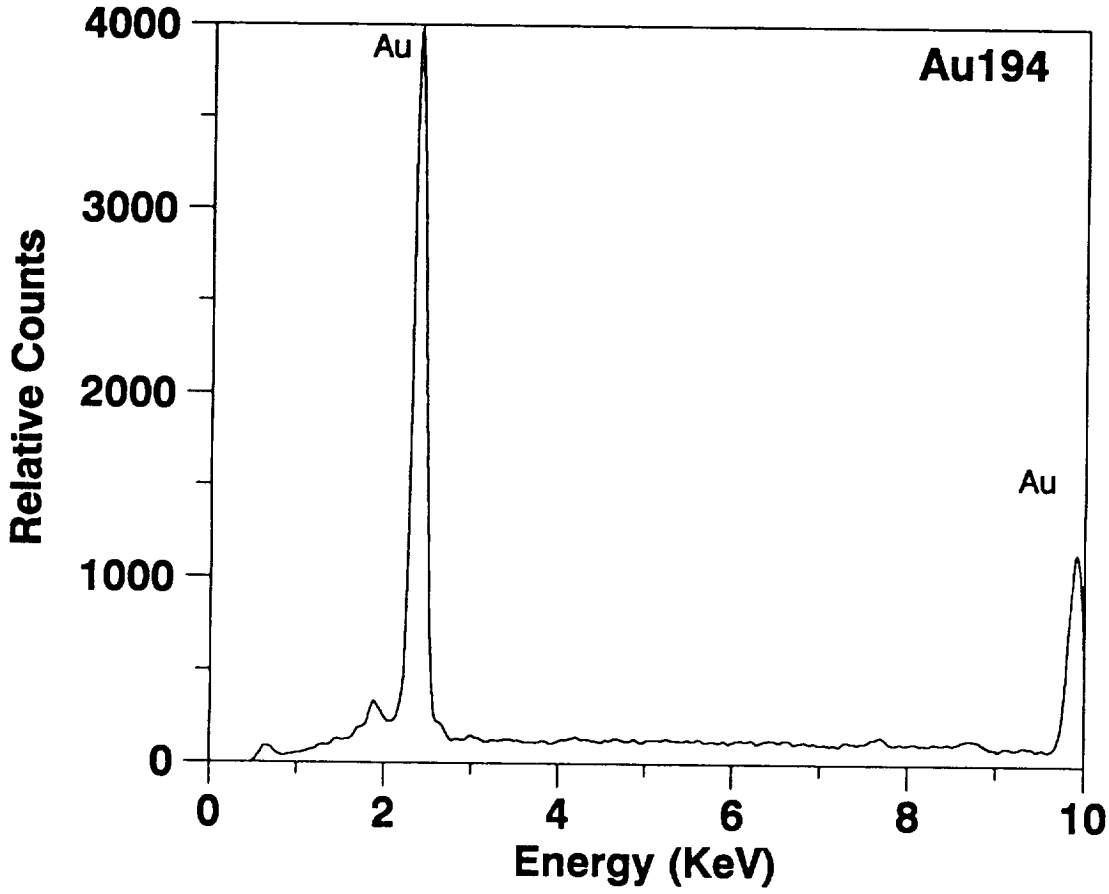
COMPONENT: EOOH
FEATURE: 194
CORE: LD-153

DIAMETER: 55 μm
ORIGIN: Unknown



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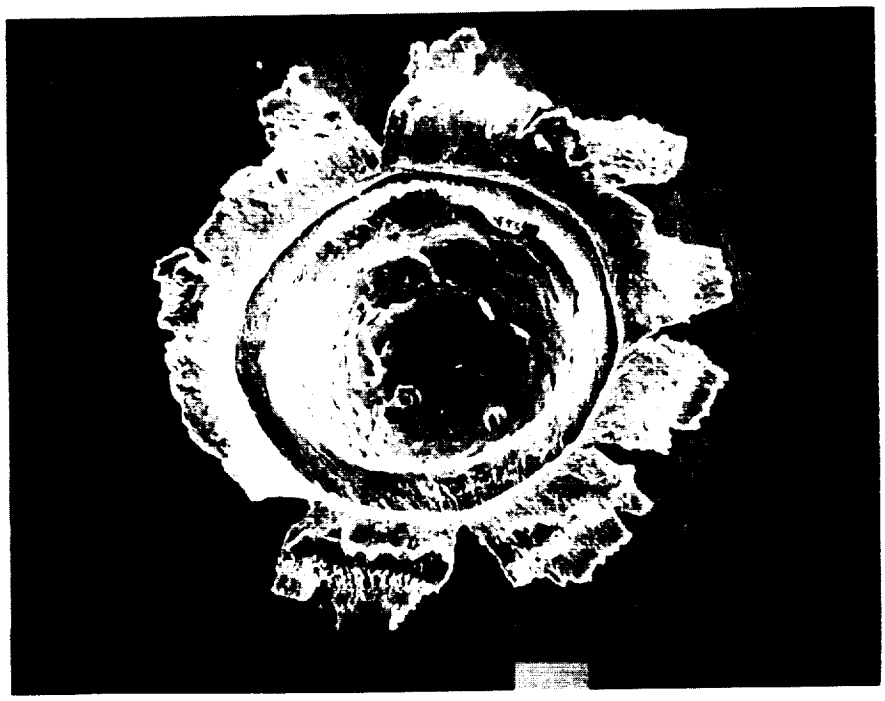
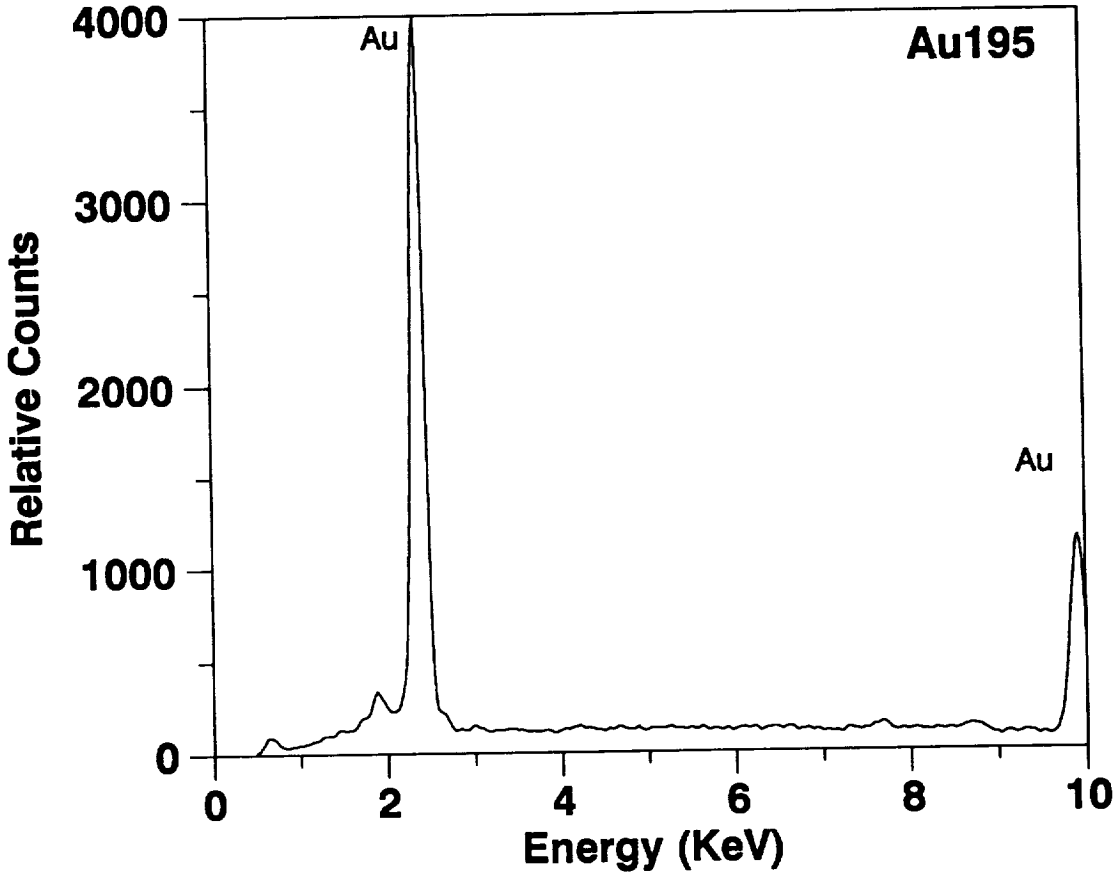


COMPONENT: EOOH
FEATURE: 195
CORE: LD-151

DIAMETER: 65 μm
ORIGIN: Unknown



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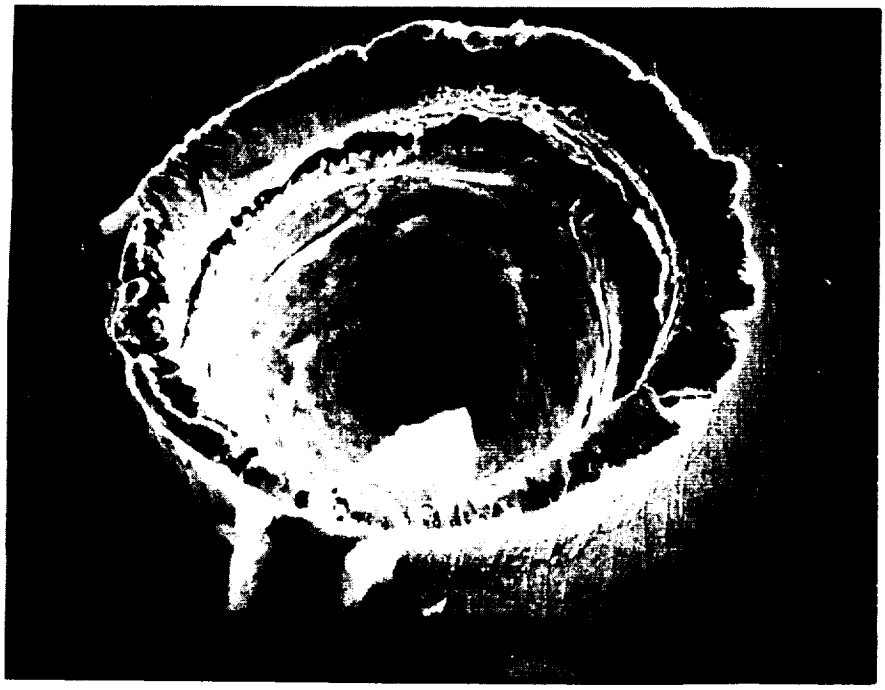
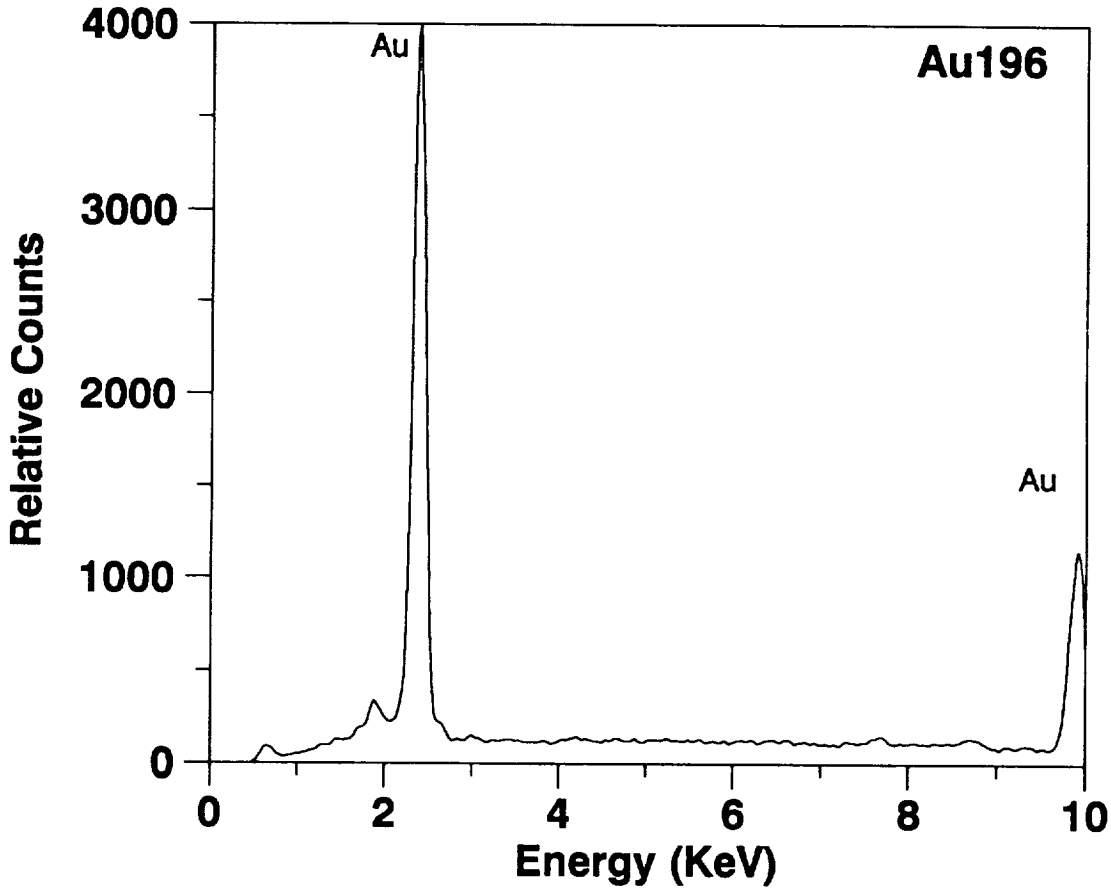


COMPONENT: EOOH
FEATURE: 196
CORE: LD-154

DIAMETER: 30 μm
ORIGIN: Unknown



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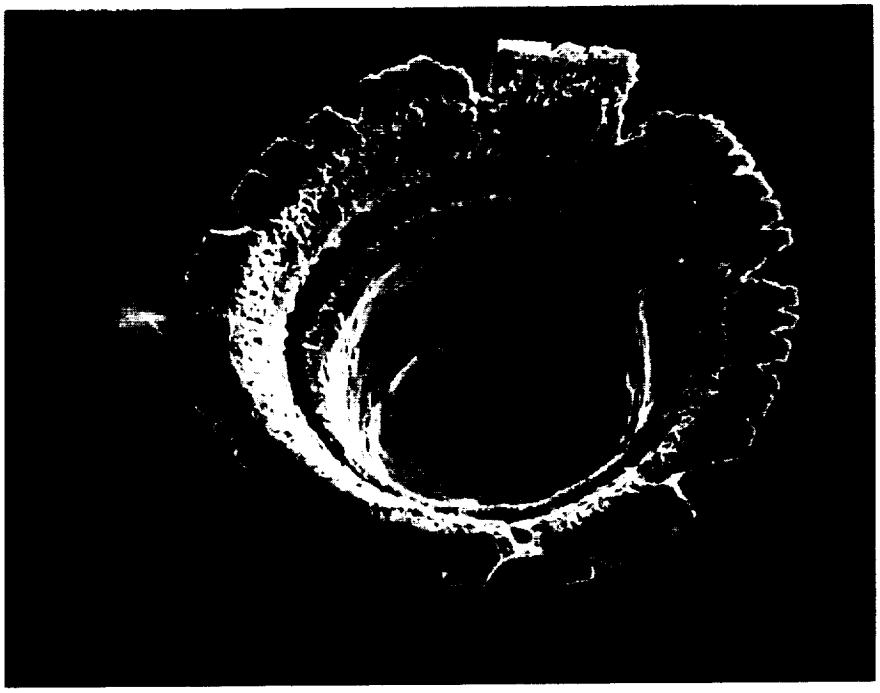
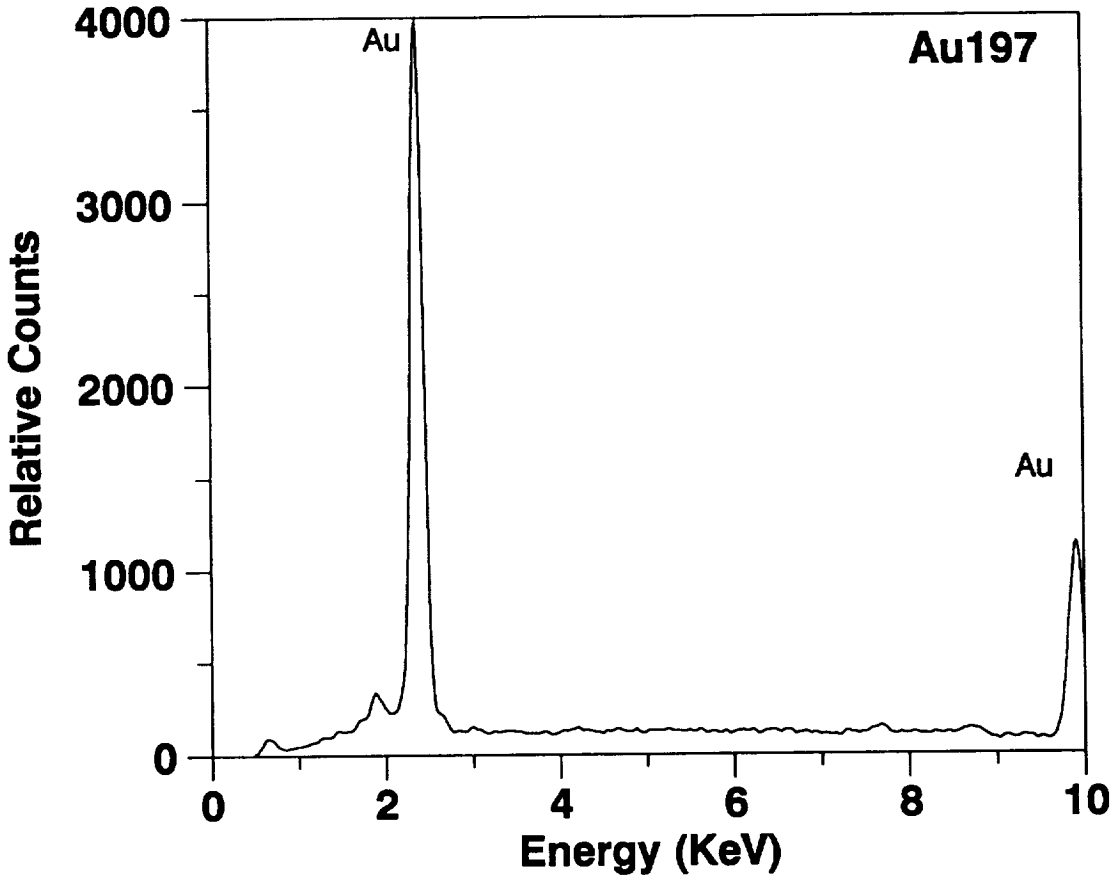


COMPONENT: EOOH
FEATURE: 197
CORE: LD-146

DIAMETER: 55 μm
ORIGIN: Unknown



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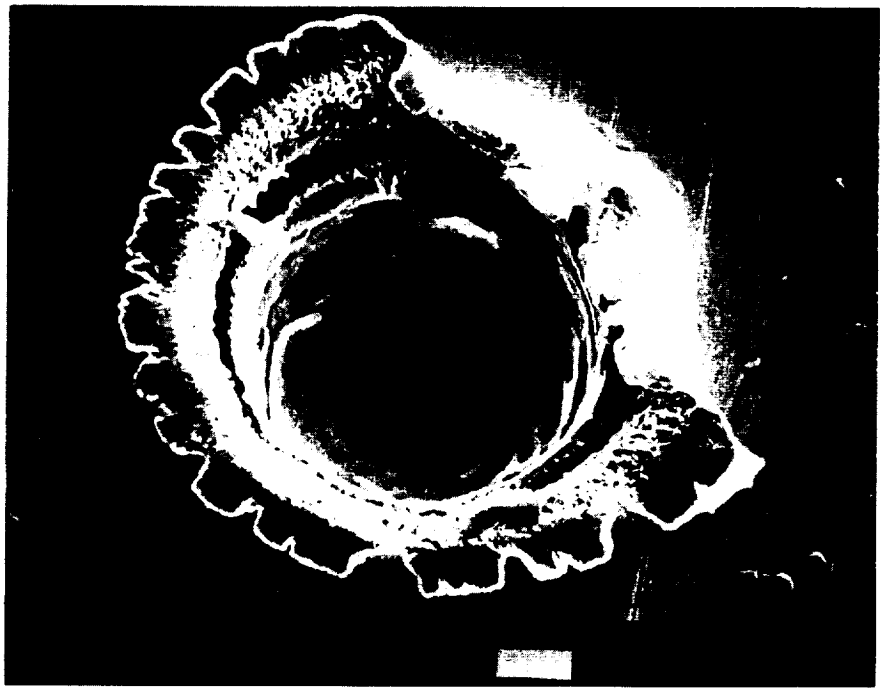
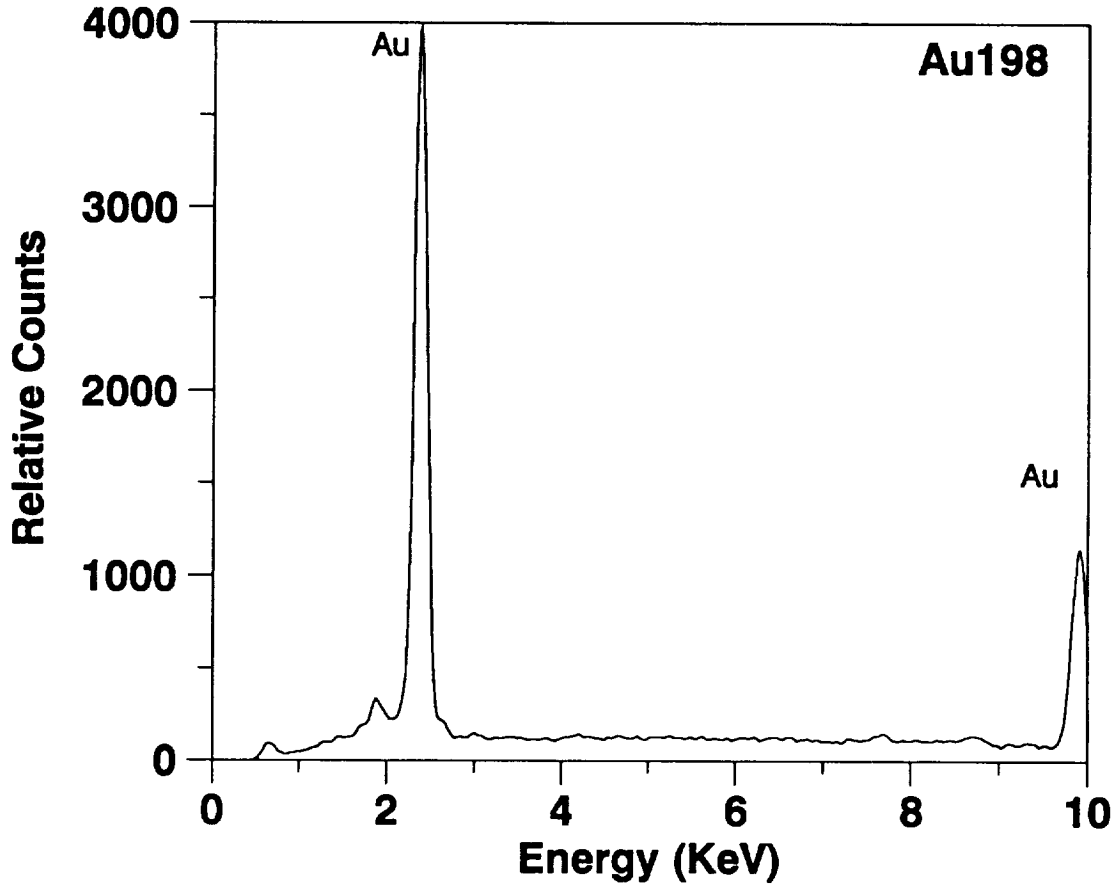


COMPONENT: EOOH
FEATURE: 198
CORE: LD-145

DIAMETER: 45 μm
ORIGIN: Unknown



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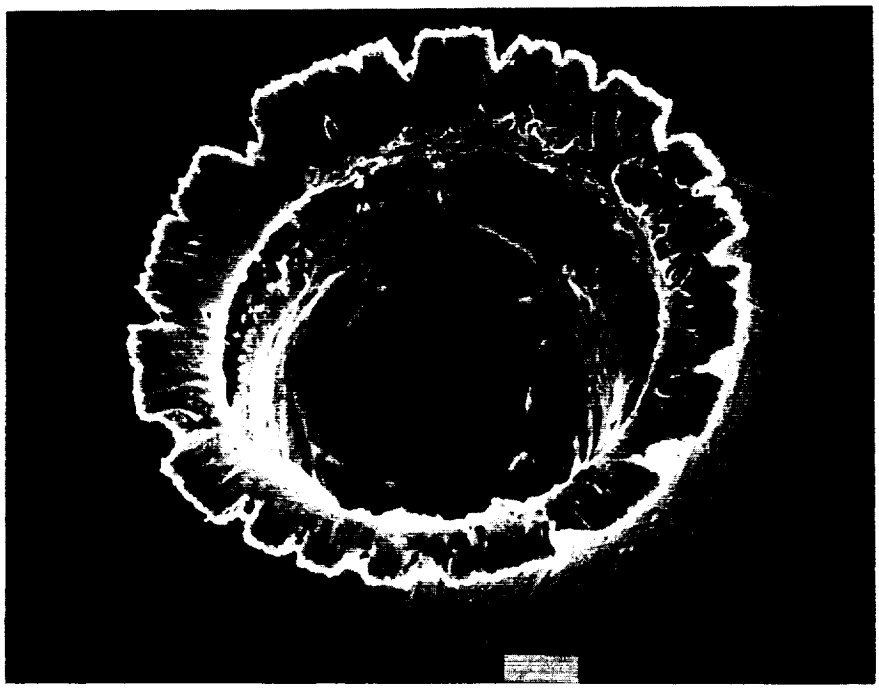
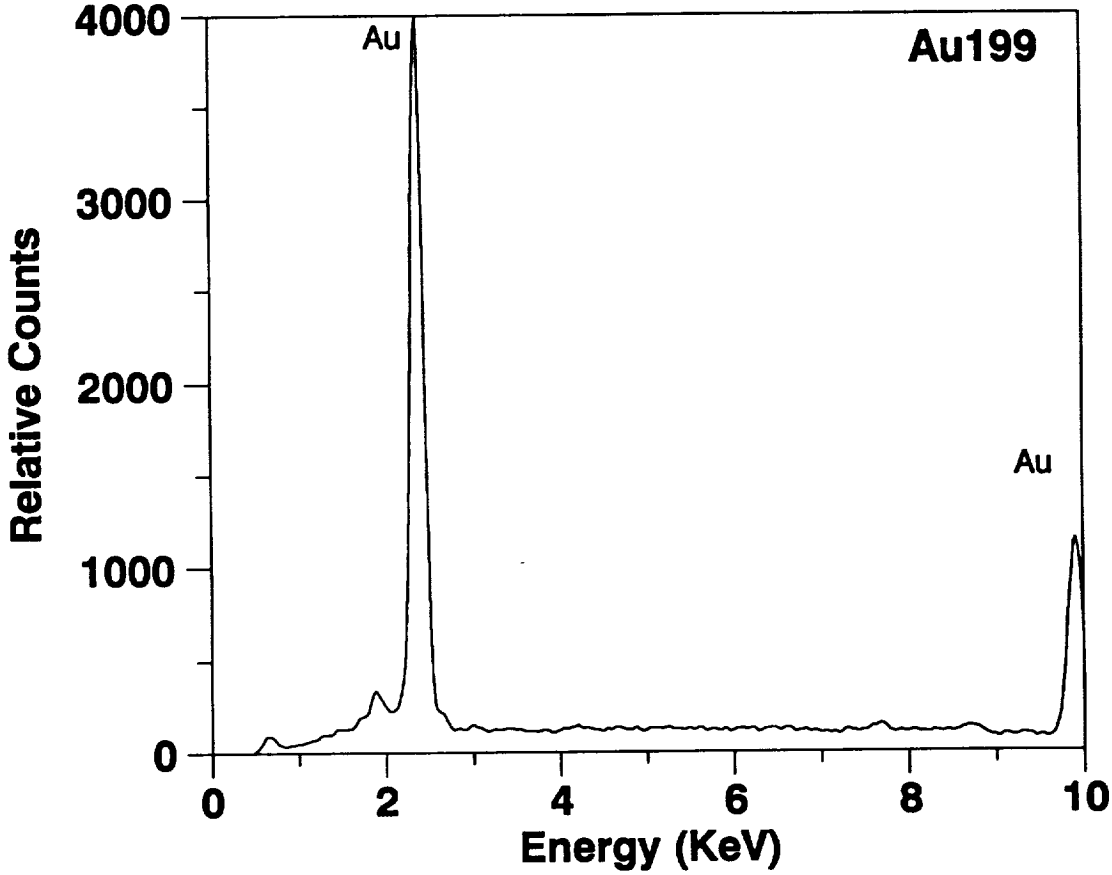


COMPONENT: EOOH
FEATURE: 199
CORE: LD-144

DIAMETER: 20 μm
ORIGIN: Unknown



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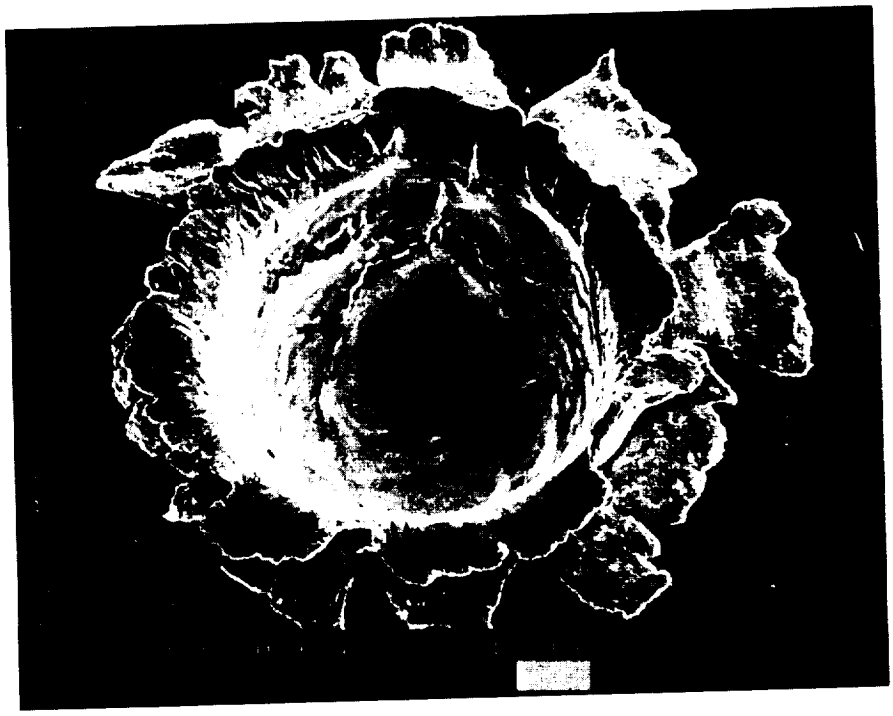
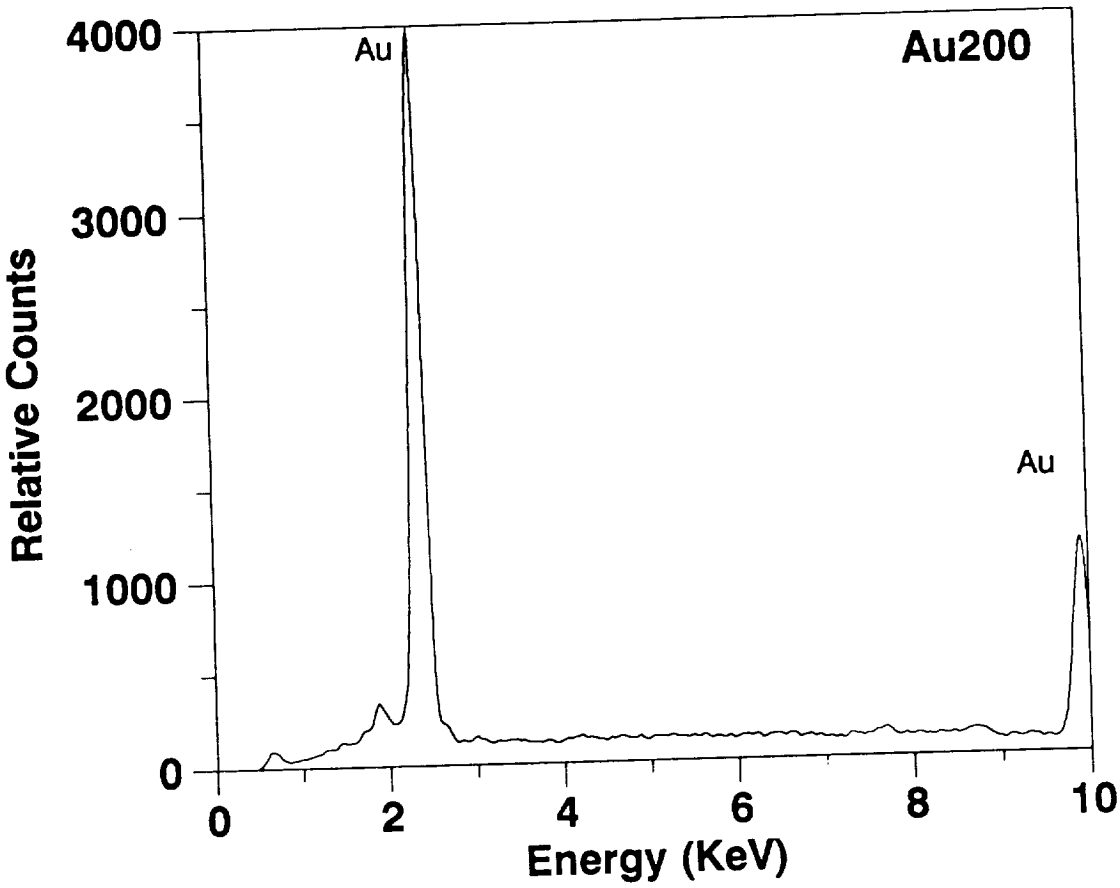


COMPONENT: EOOH
FEATURE: 200
CORE: LD-143

DIAMETER: 95 μm
ORIGIN: Unknown



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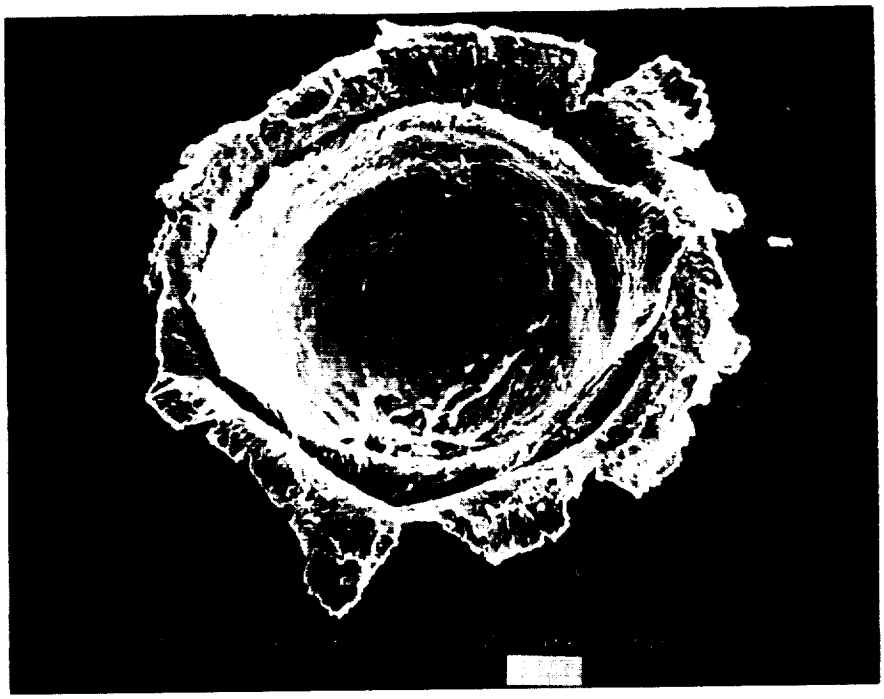
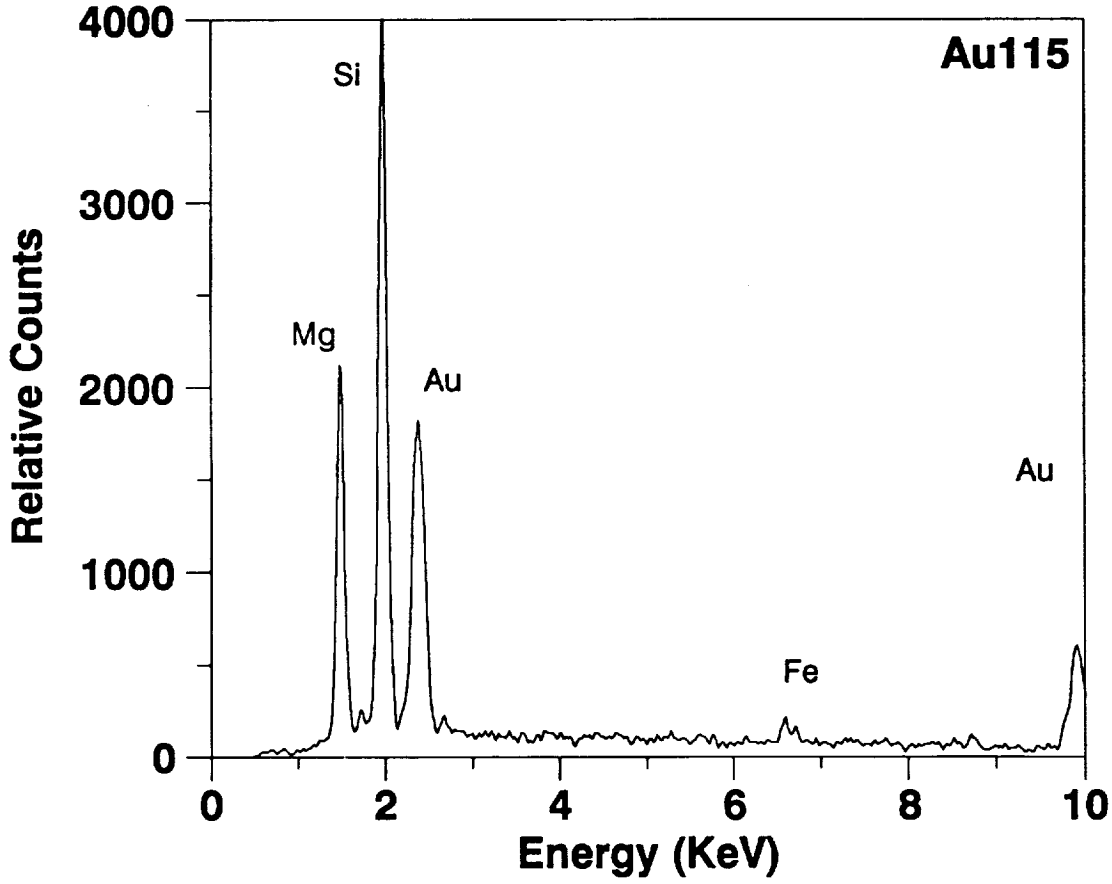


COMPONENT: EOOH
FEATURE: 201
CORE: LD-150

DIAMETER: 55 μm
ORIGIN: Natural



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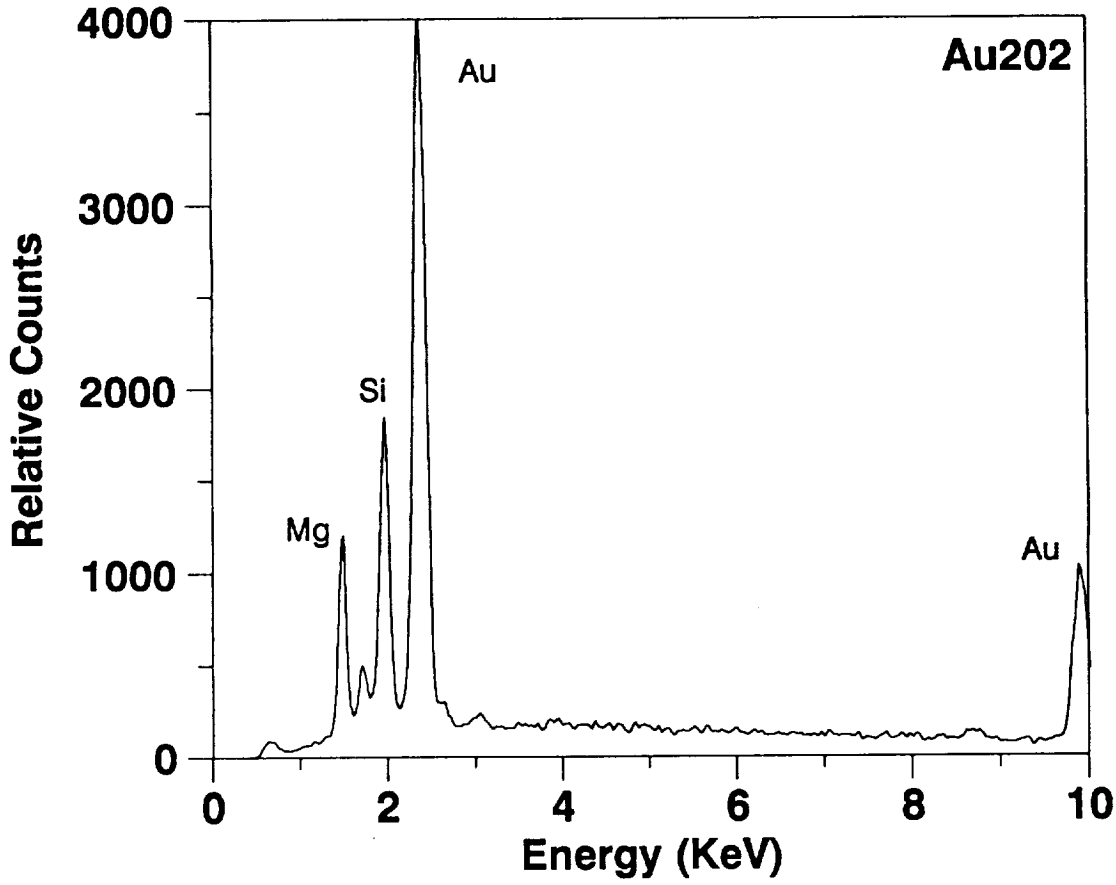
COMPONENT: EOOH
FEATURE: 202
CORE: LD-141

DIAMETER: 20 μm
ORIGIN: Natural



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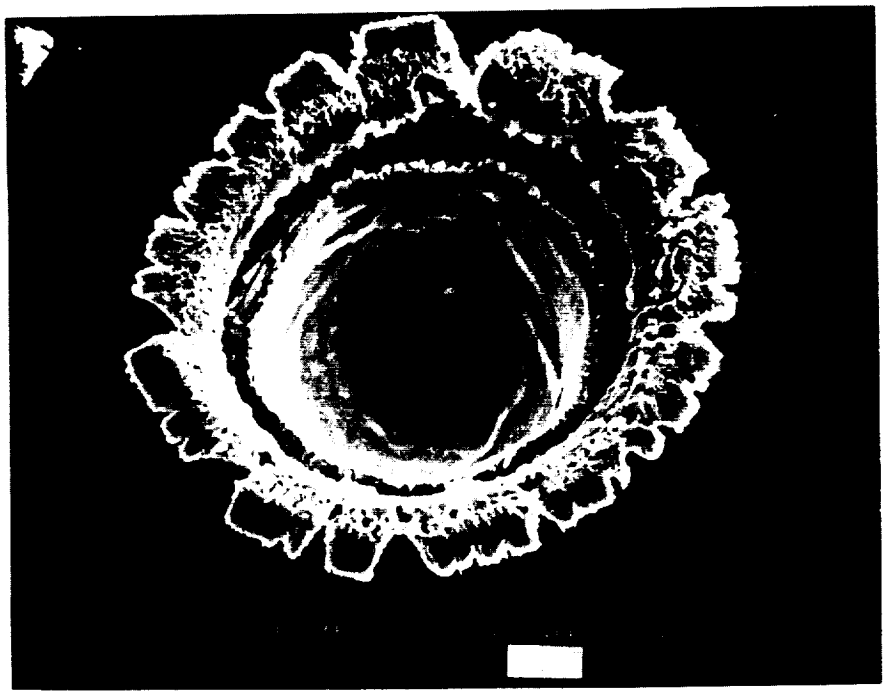
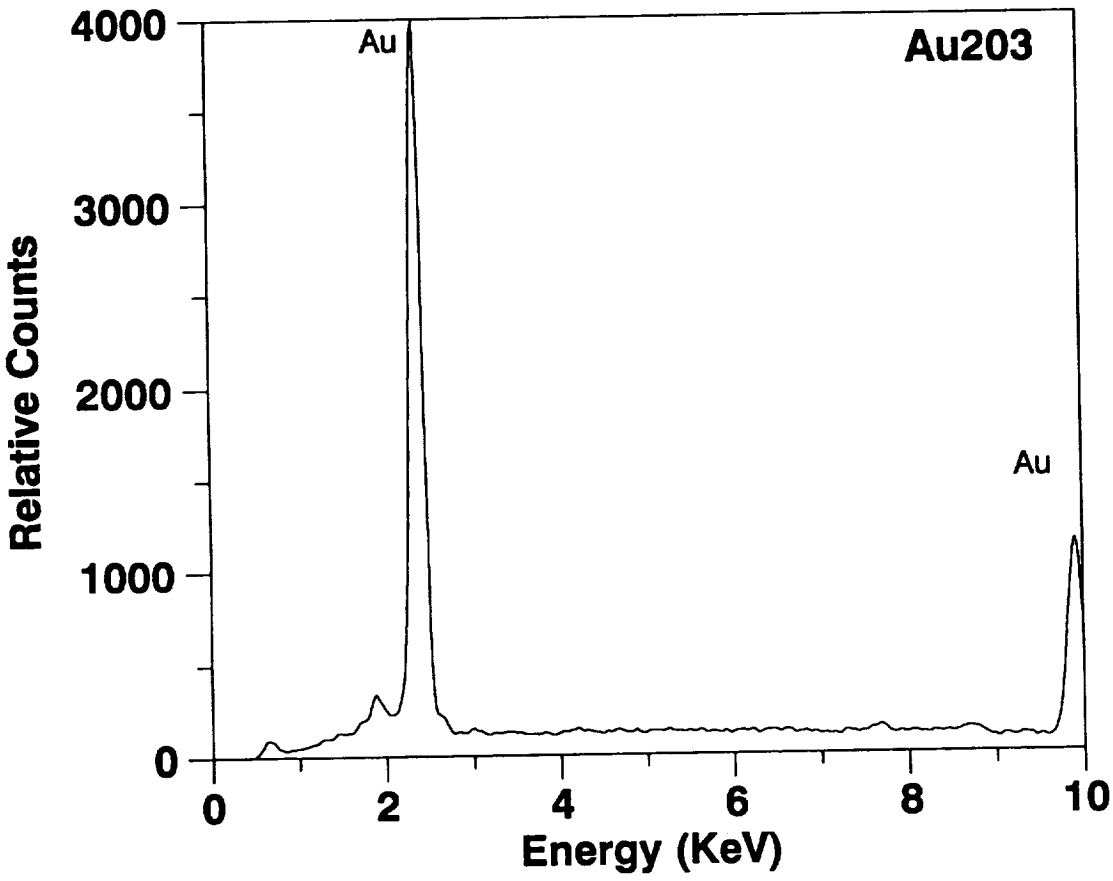


COMPONENT: EOOH
FEATURE: 203
CORE: LD-149

DIAMETER: 30 μm
ORIGIN: Unknown



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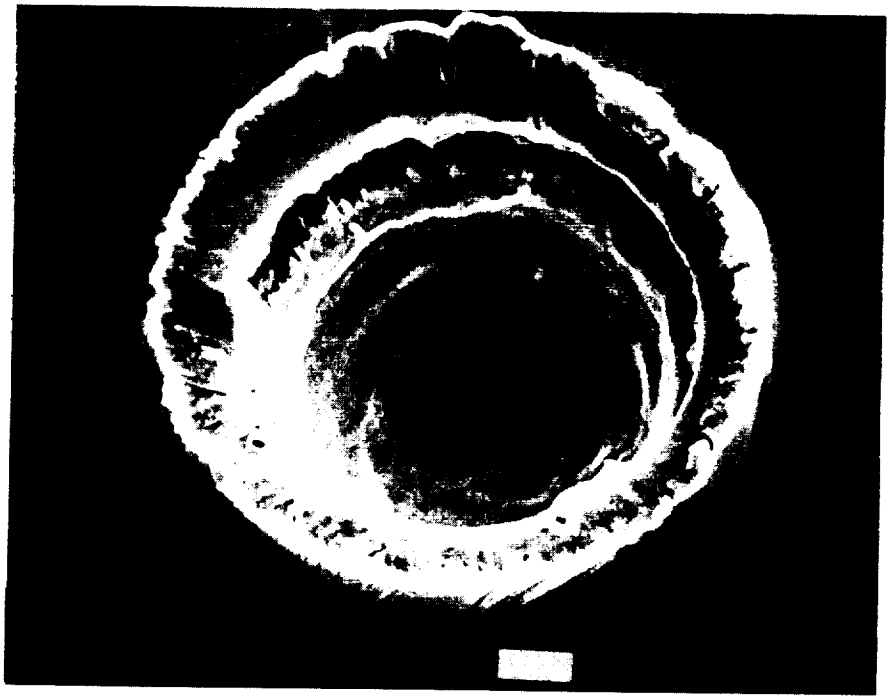
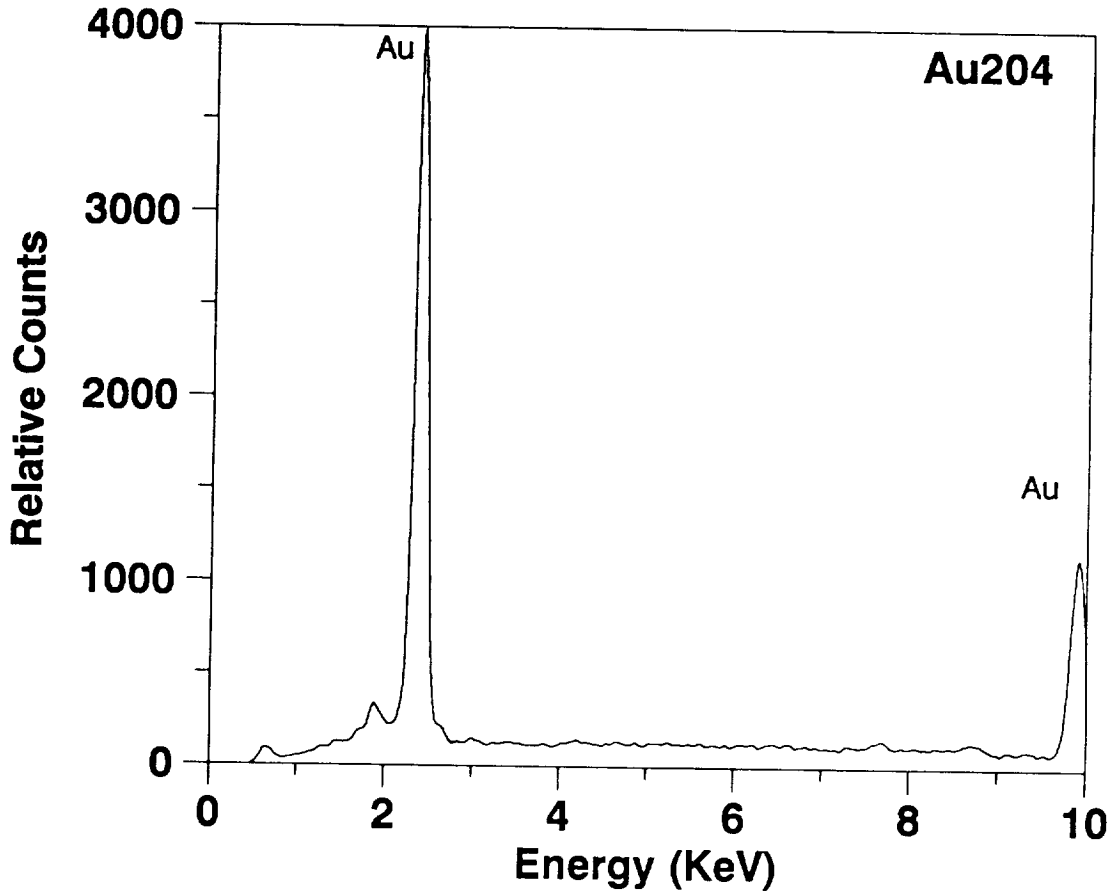


COMPONENT: EOOH
FEATURE: 204
CORE: LD-142

DIAMETER: 15 μm
ORIGIN: Unknown



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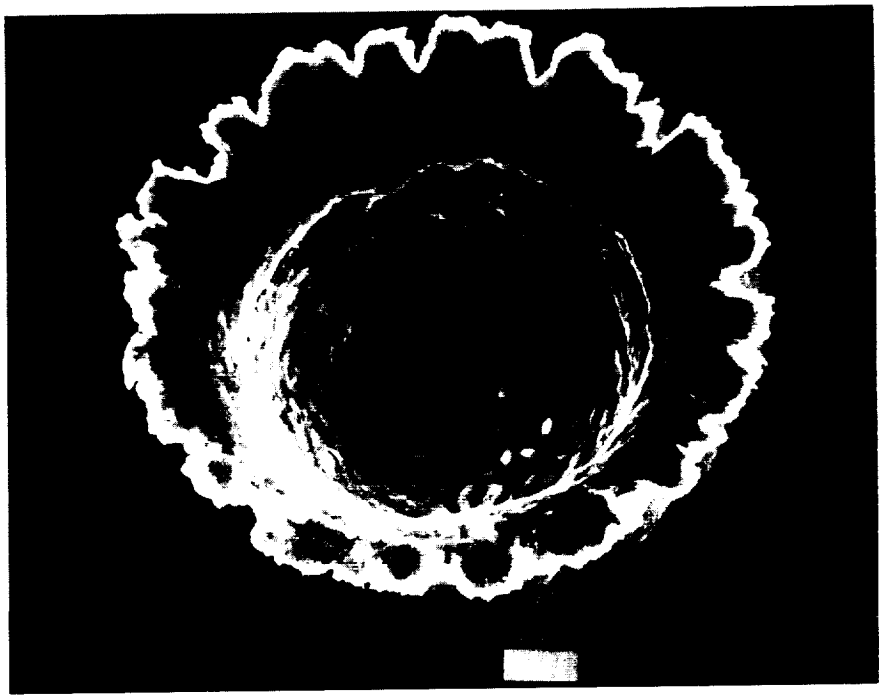
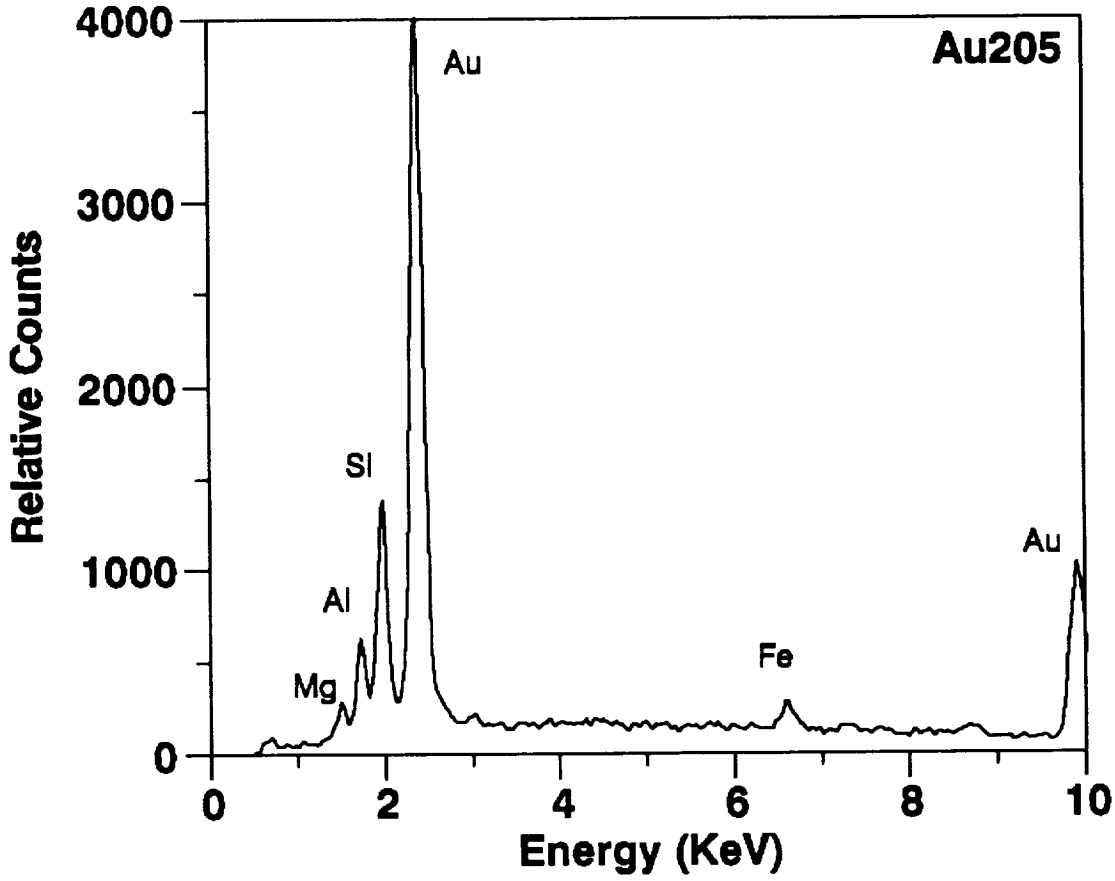


COMPONENT: EOOE
FEATURE: 205
CORE: LD-137

DIAMETER: 15 μm
ORIGIN: Natural



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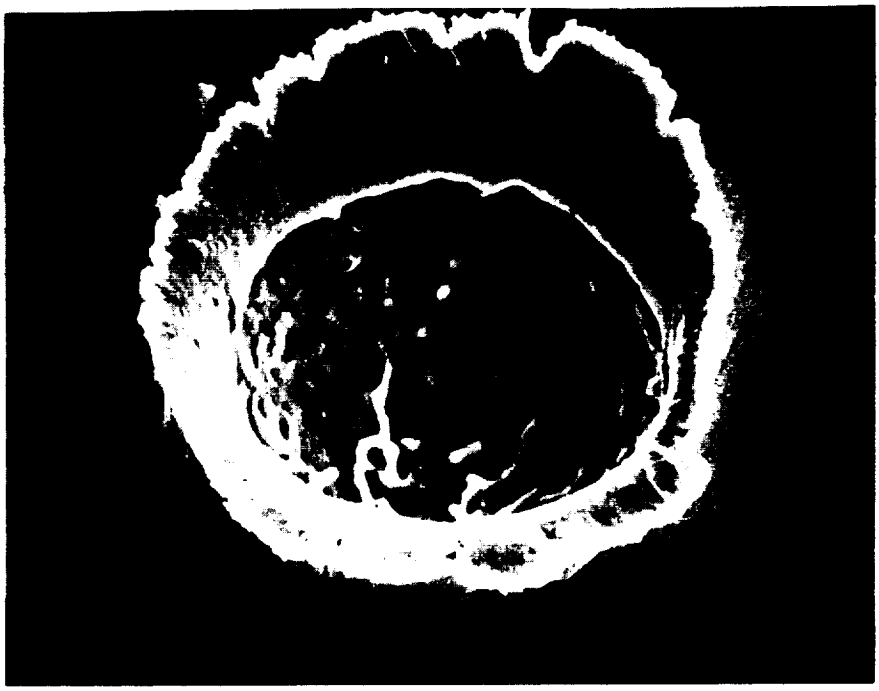
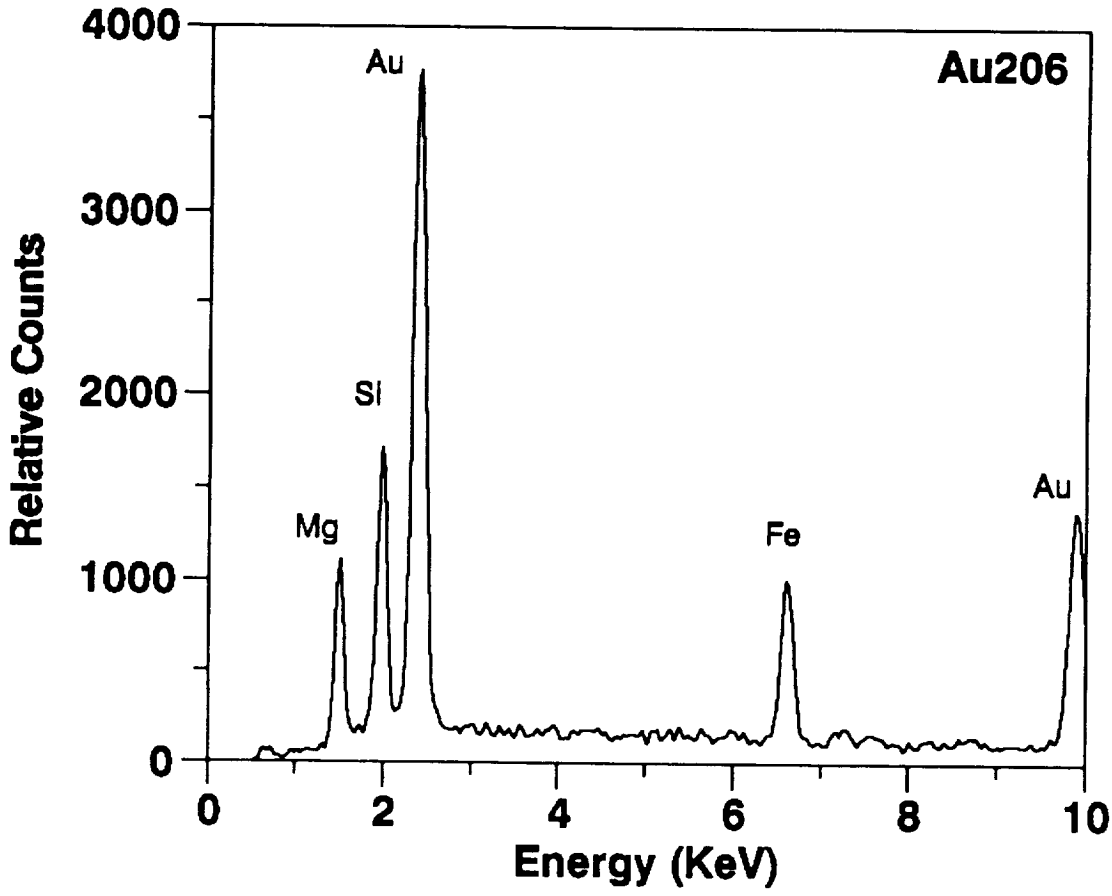


COMPONENT: EOOE
FEATURE: 206
CORE: LD-138

DIAMETER: 10 μm
ORIGIN: Natural



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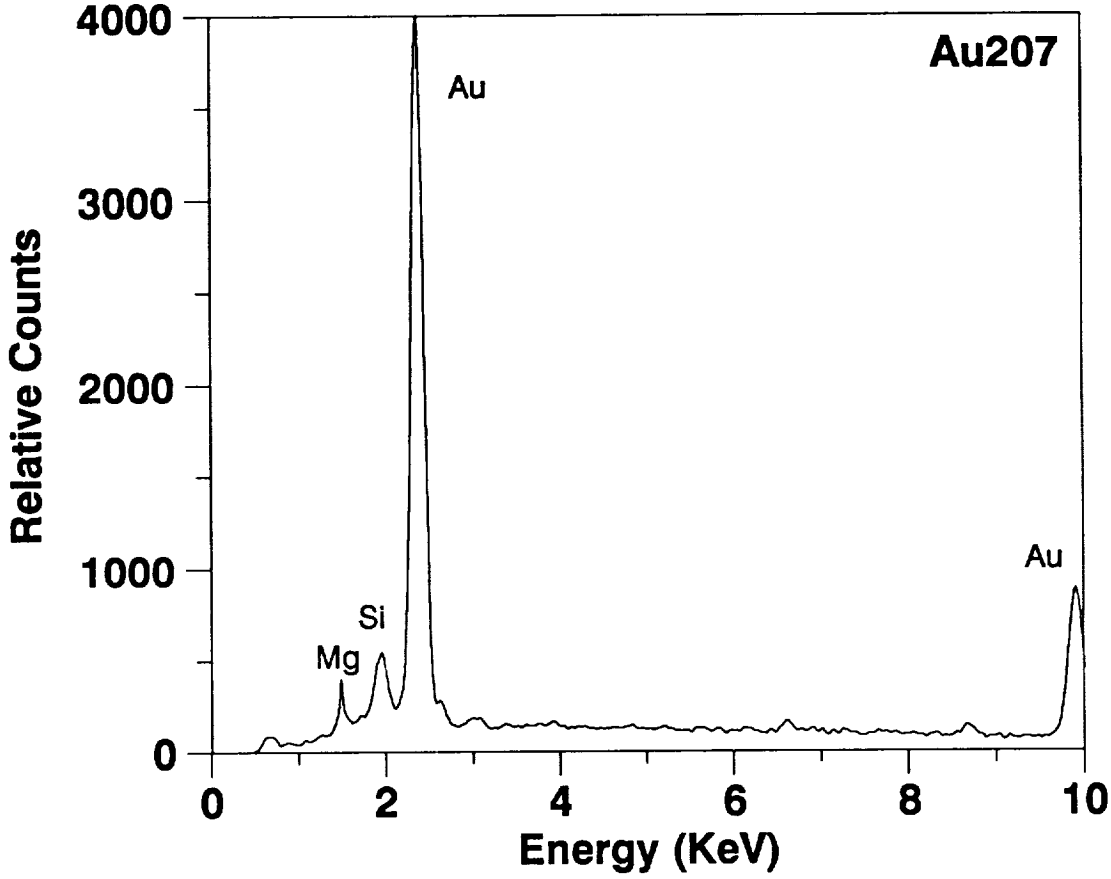
COMPONENT: EOOH
FEATURE: 207
CORE: LD-147

DIAMETER: 15 μm
ORIGIN: Natural



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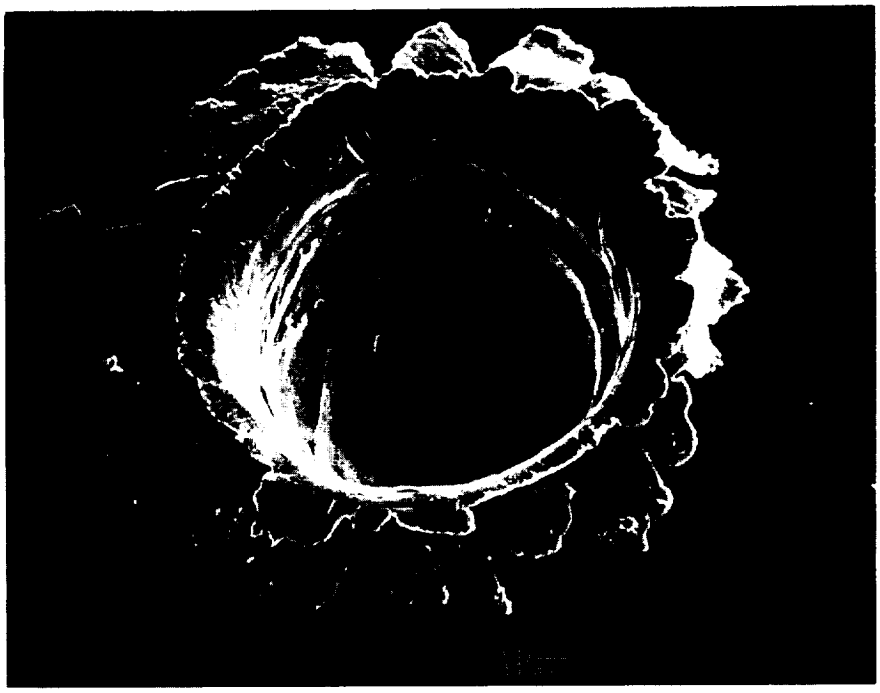
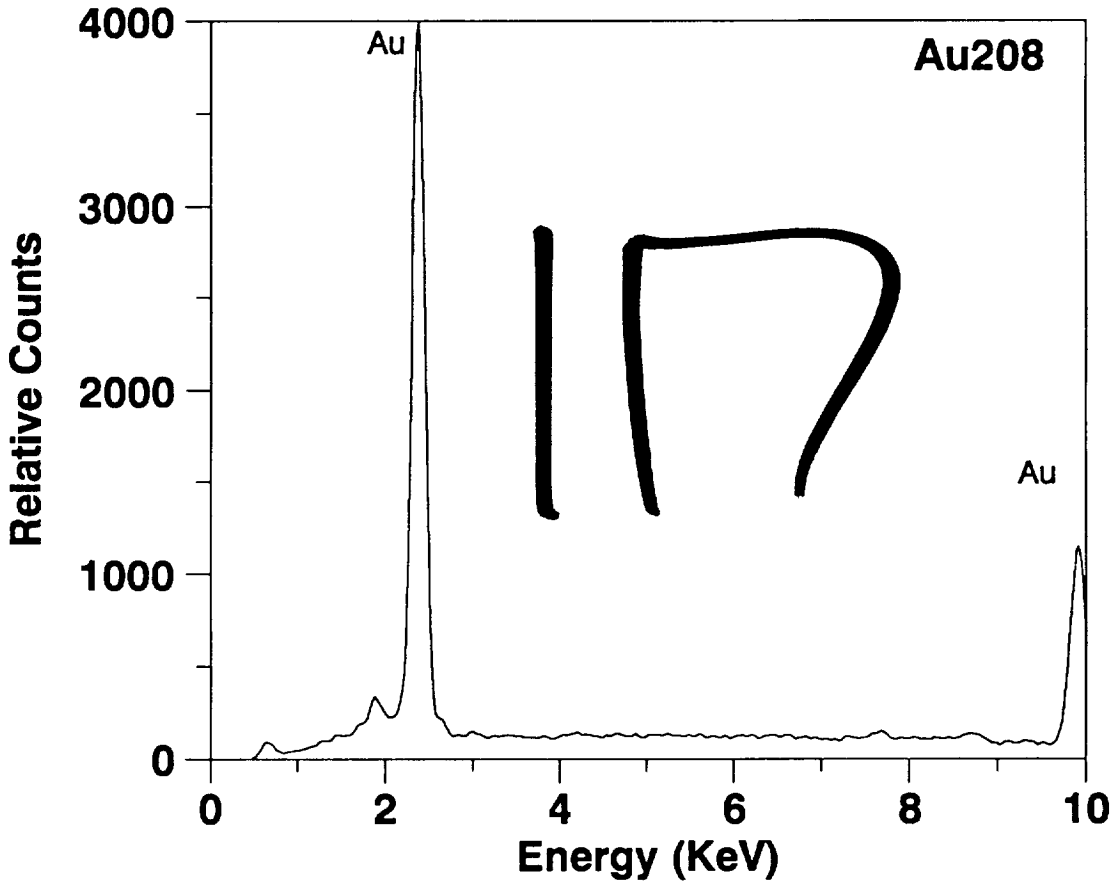


COMPONENT: EOOH
FEATURE: 208
CORE: LD-139

DIAMETER: 65 μm
ORIGIN: Unknown



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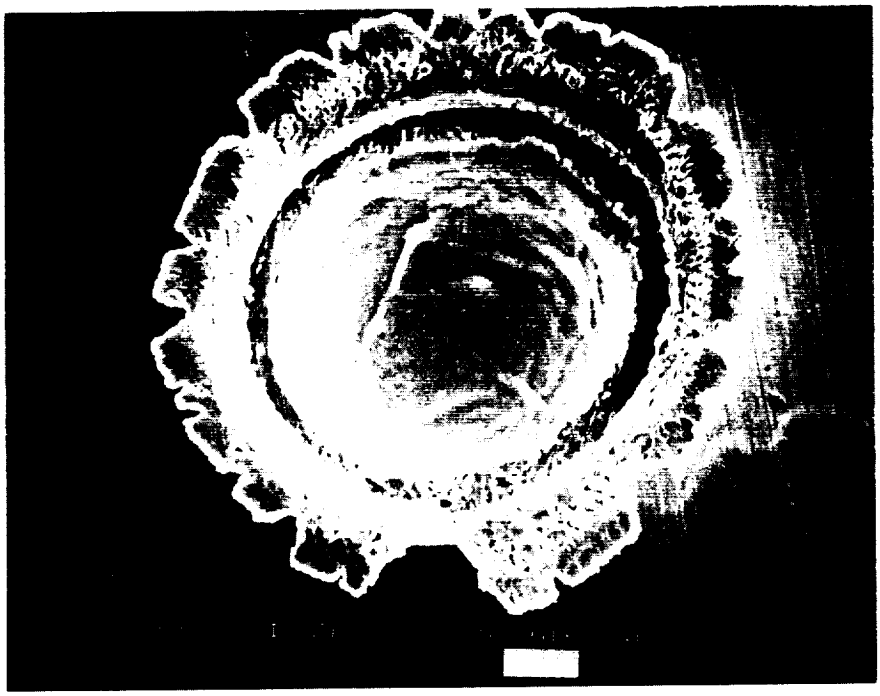
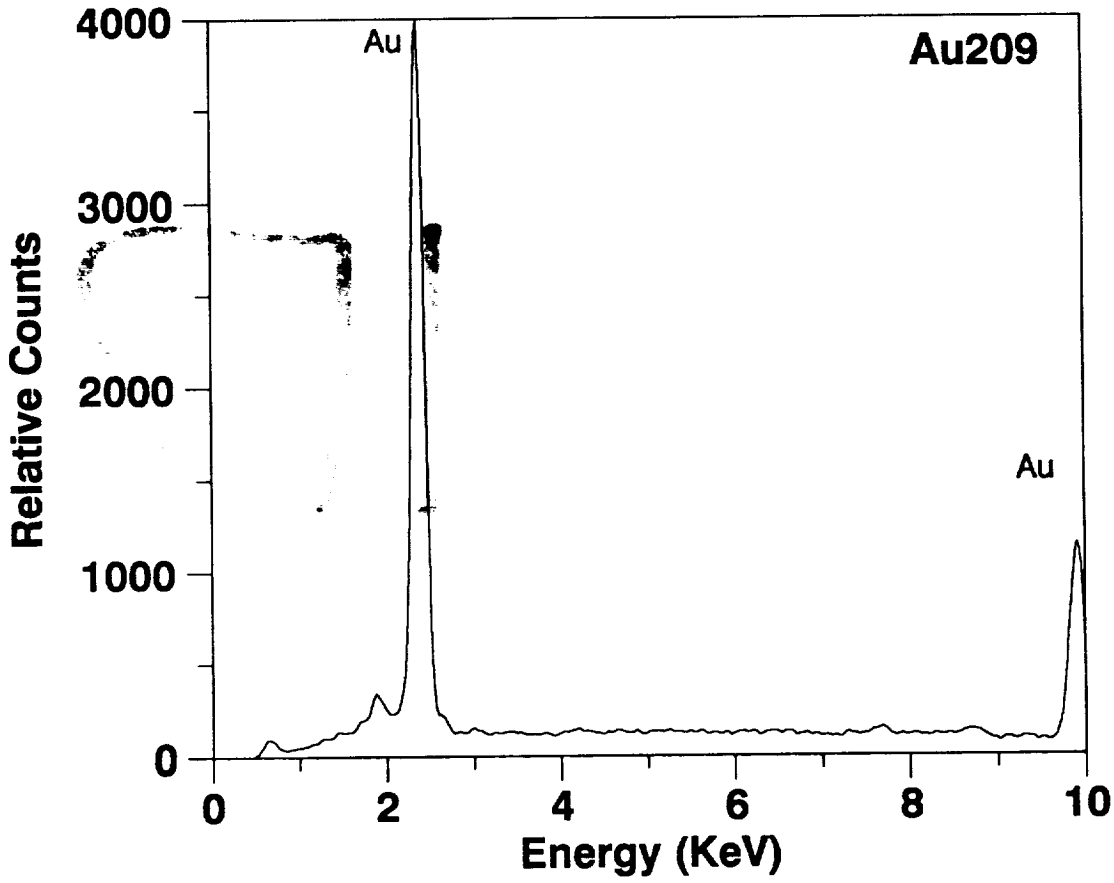


COMPONENT: EOOH
FEATURE: 209
CORE: LD-140

DIAMETER: 30 μm
ORIGIN: Unknown



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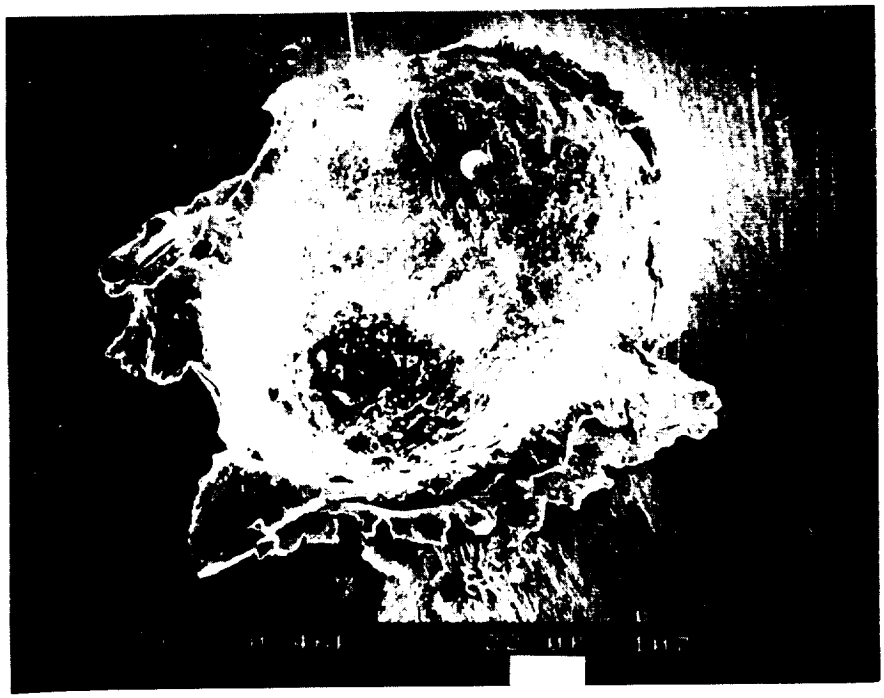
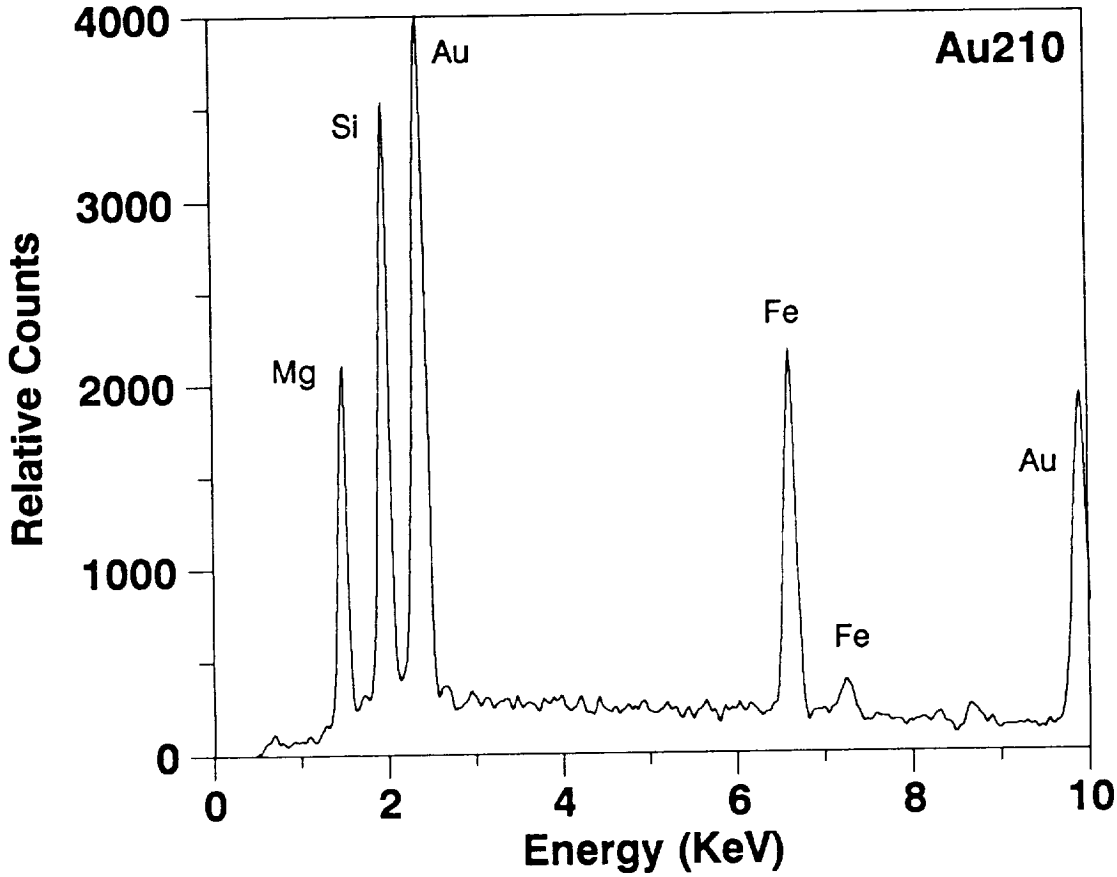


COMPONENT: EOOH
FEATURE: 210
CORE: LD-148

DIAMETER: 115 μm
ORIGIN: Natural



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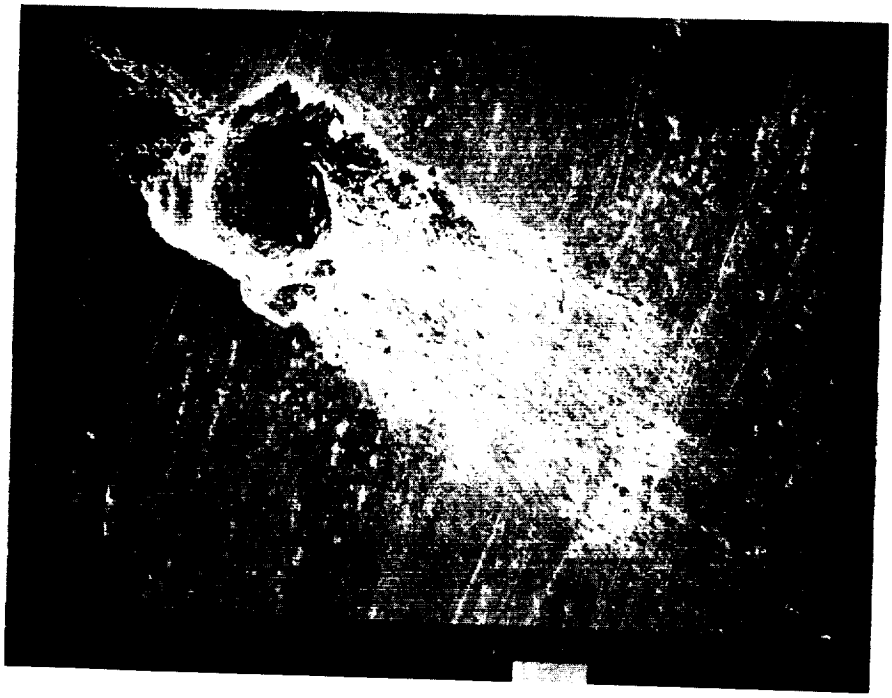
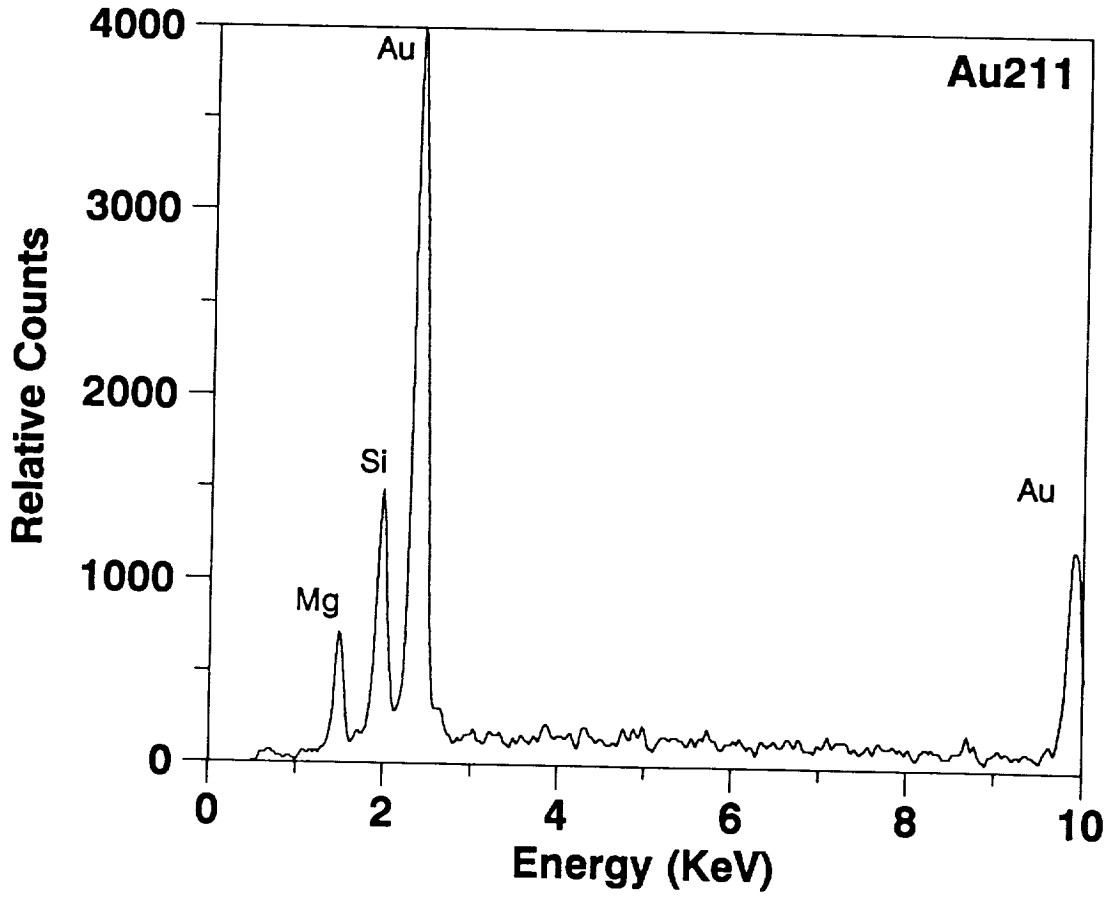


COMPONENT: EOOI
FEATURE: 211
CORE: LD-196

DIAMETER: 40 μm
ORIGIN: Natural



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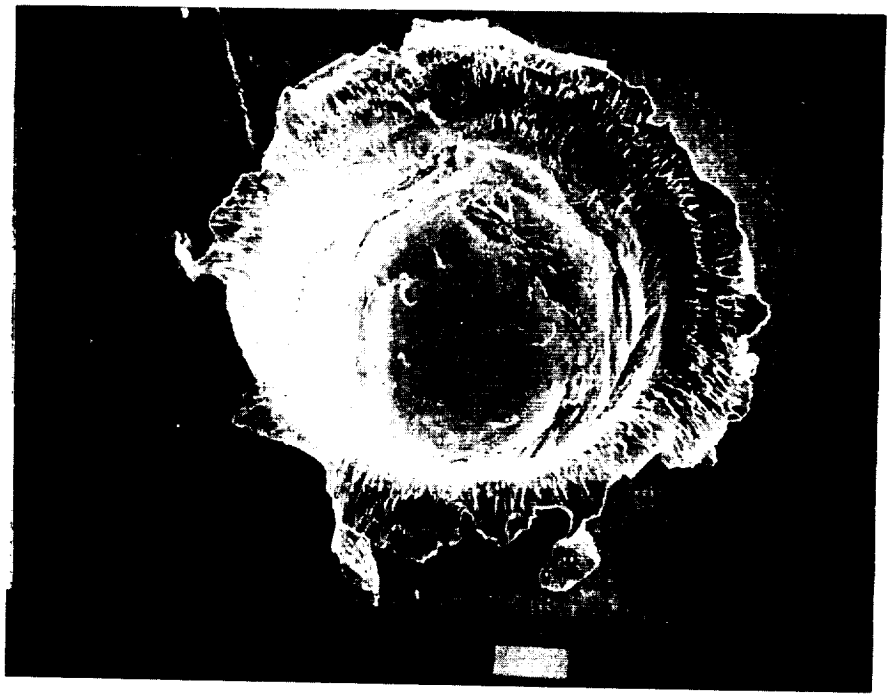
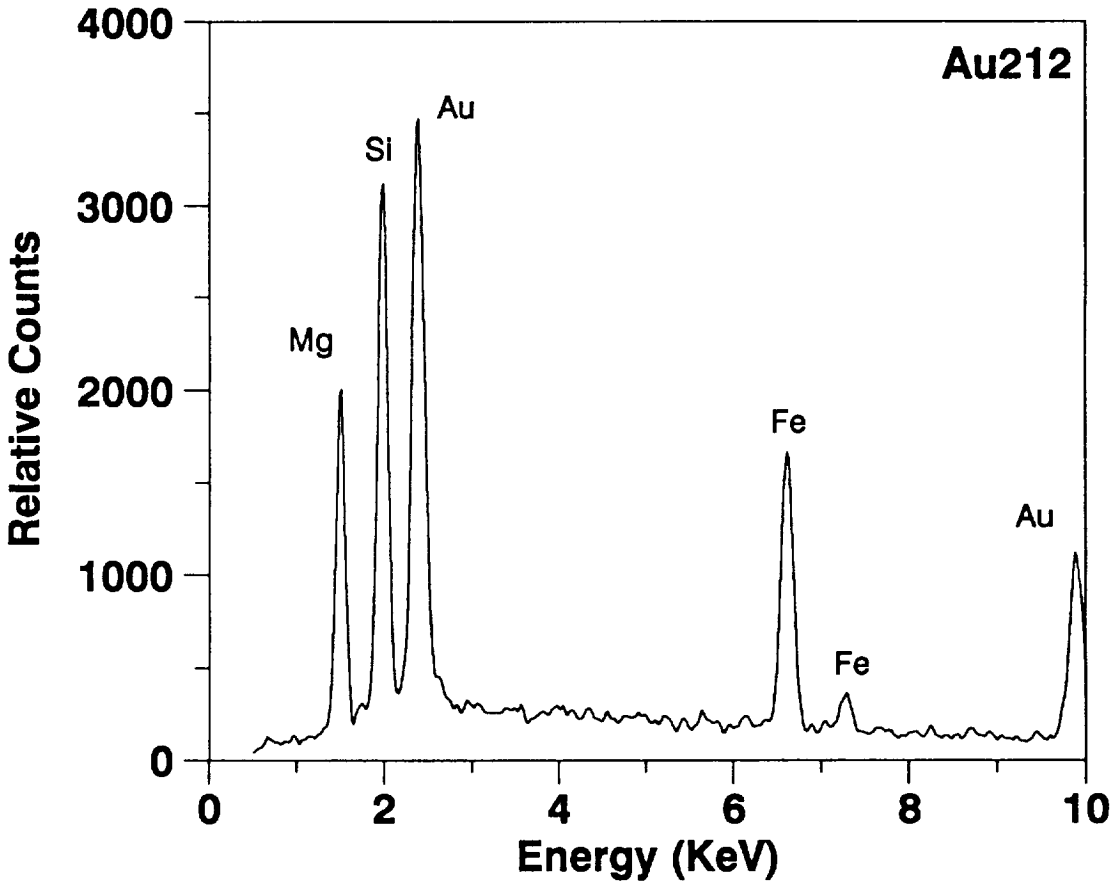


COMPONENT: EOOI
FEATURE: 212
CORE: LD-164

DIAMETER: 210 μm
ORIGIN: Natural



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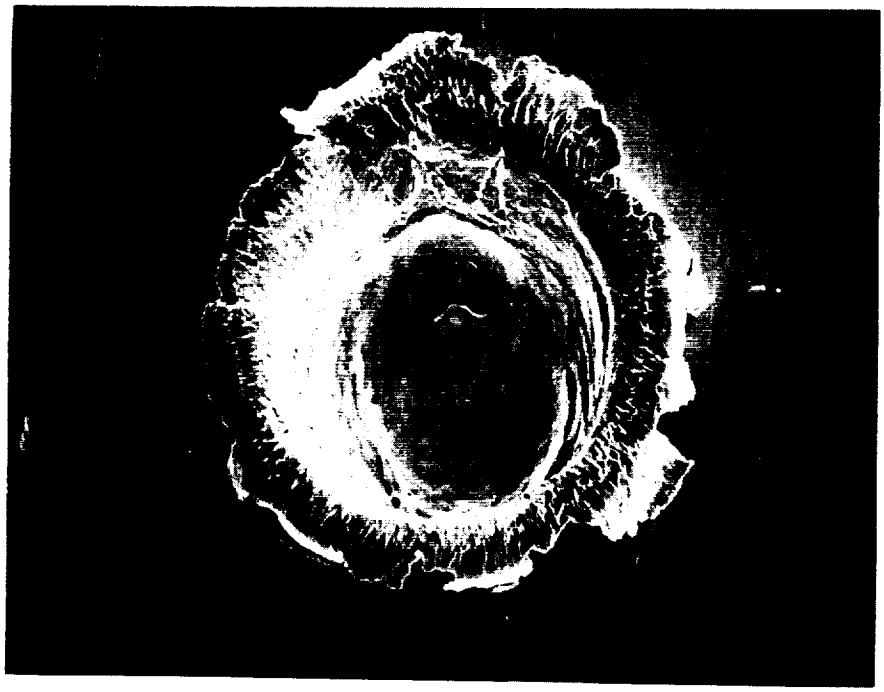
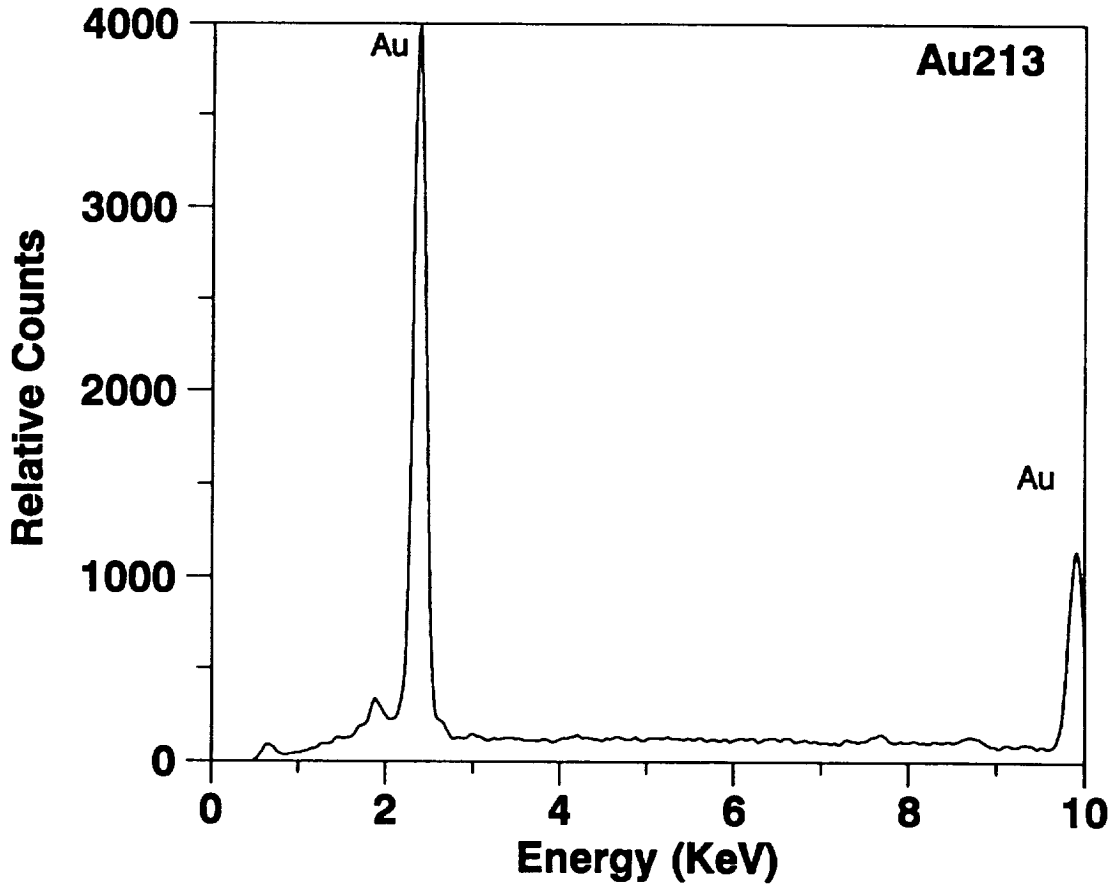


COMPONENT: E00I
FEATURE: 213
CORE: LD-167

DIAMETER: 145 μm
ORIGIN: Unknown



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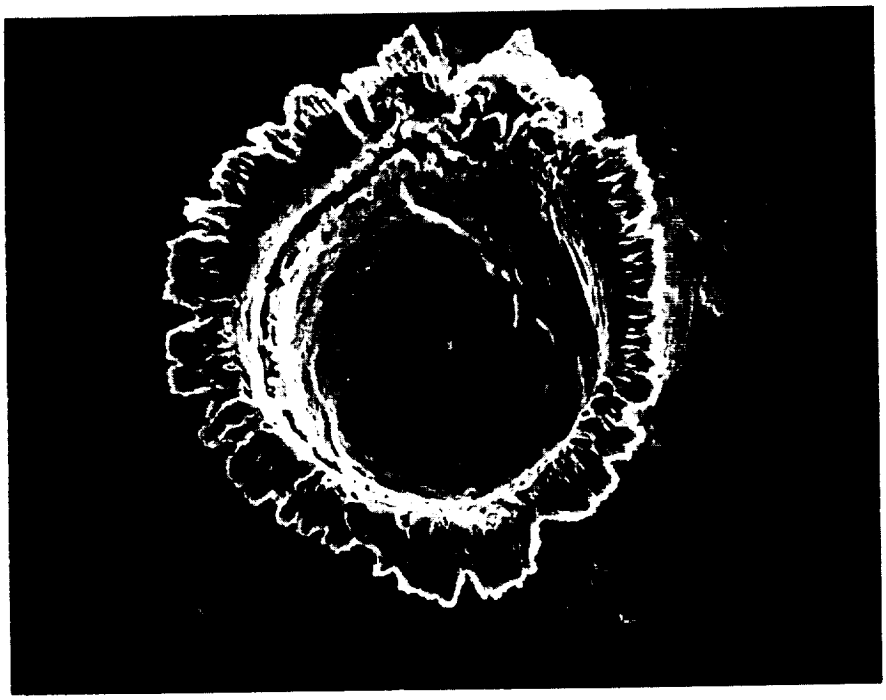
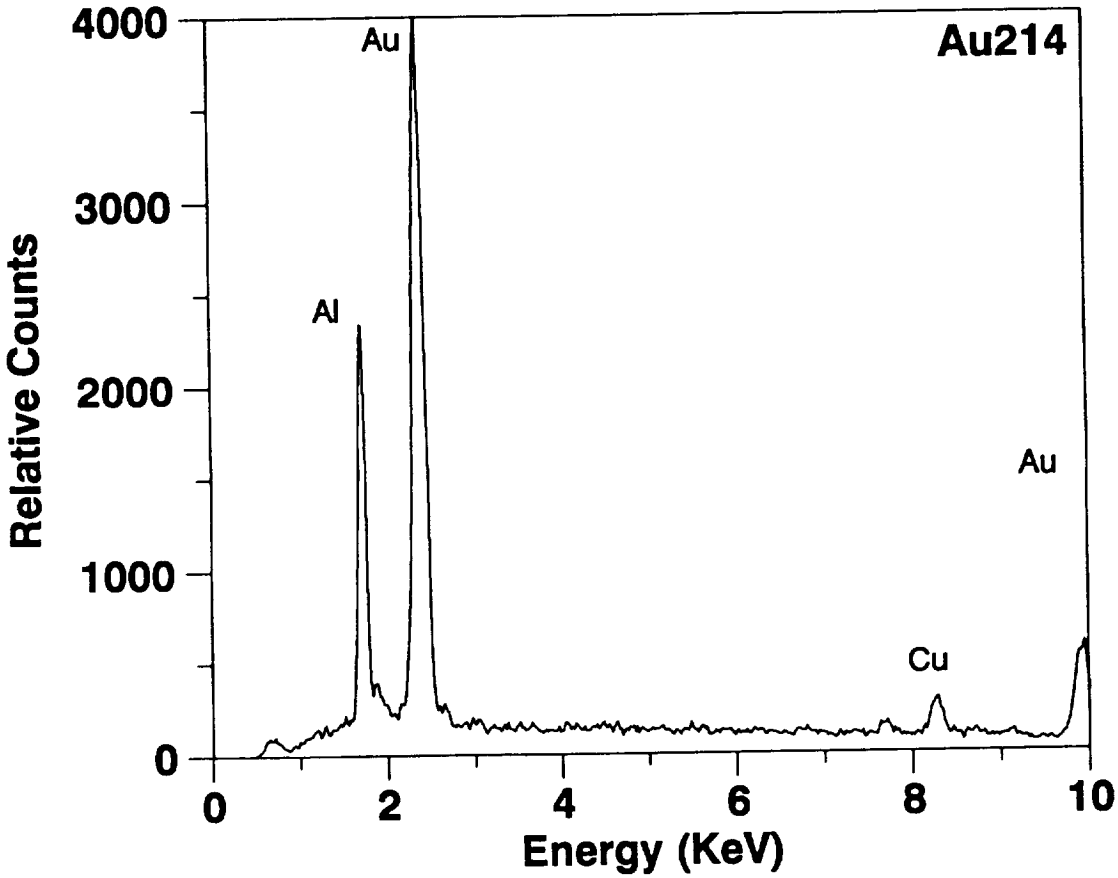


COMPONENT: EOOI
FEATURE: 214
CORE: LD-165

DIAMETER: 25 μm
ORIGIN: Man-made



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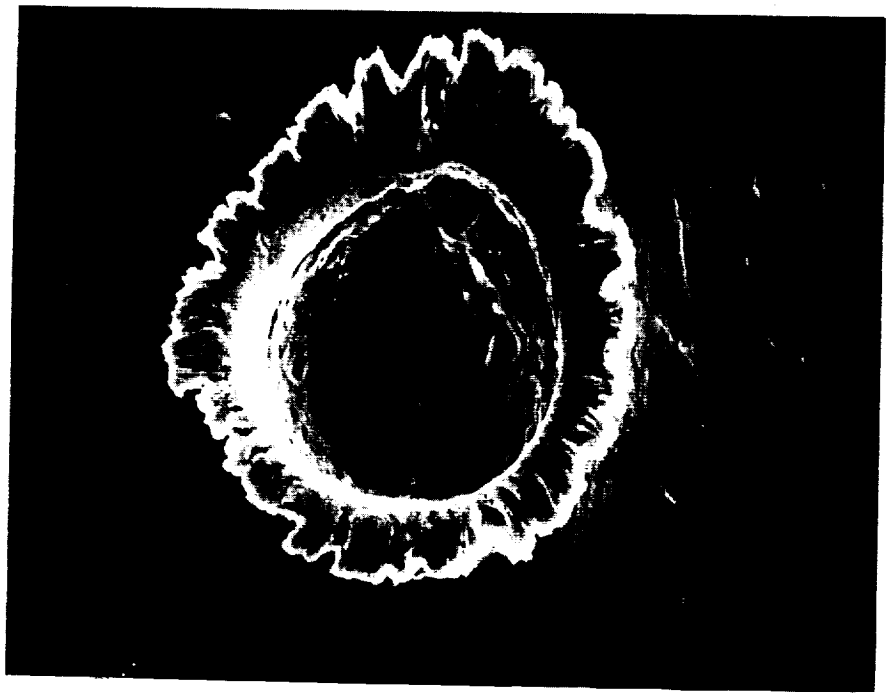
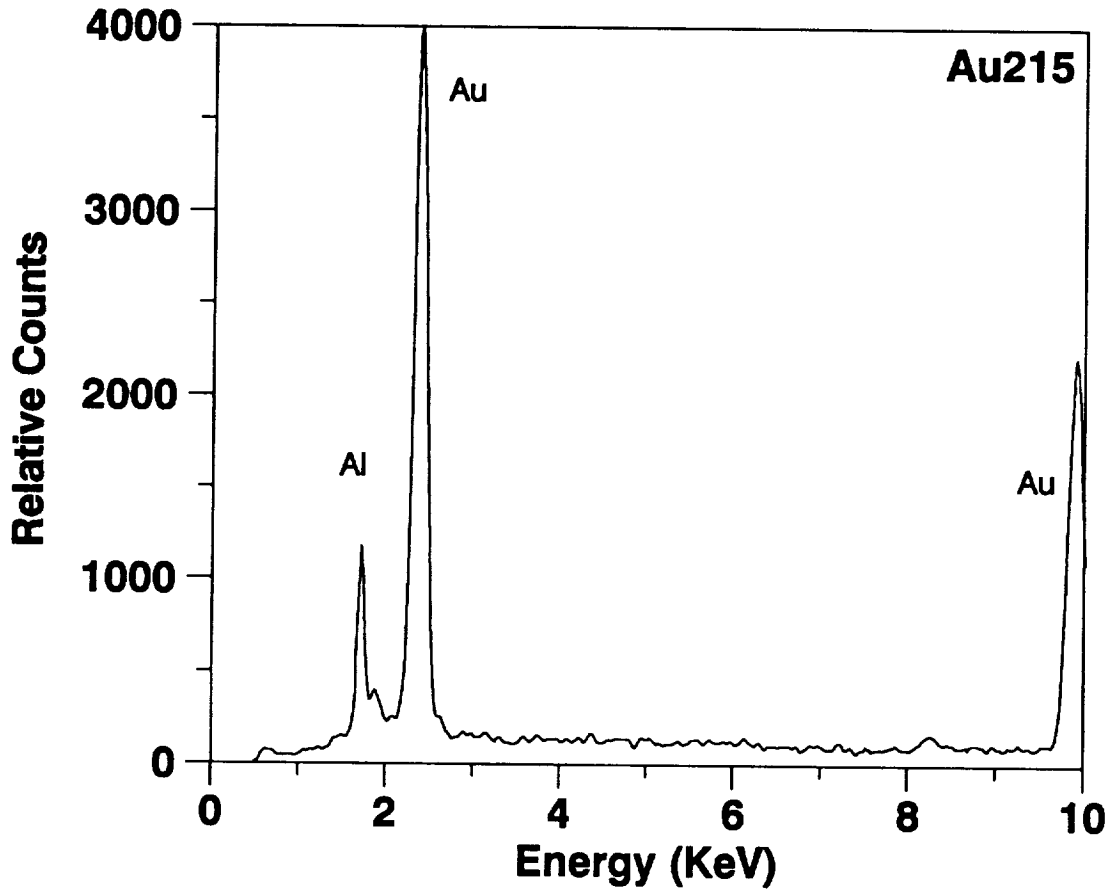


COMPONENT: EOOI
FEATURE: 215
CORE: LD-166

DIAMETER: 20 μm
ORIGIN: Man-made



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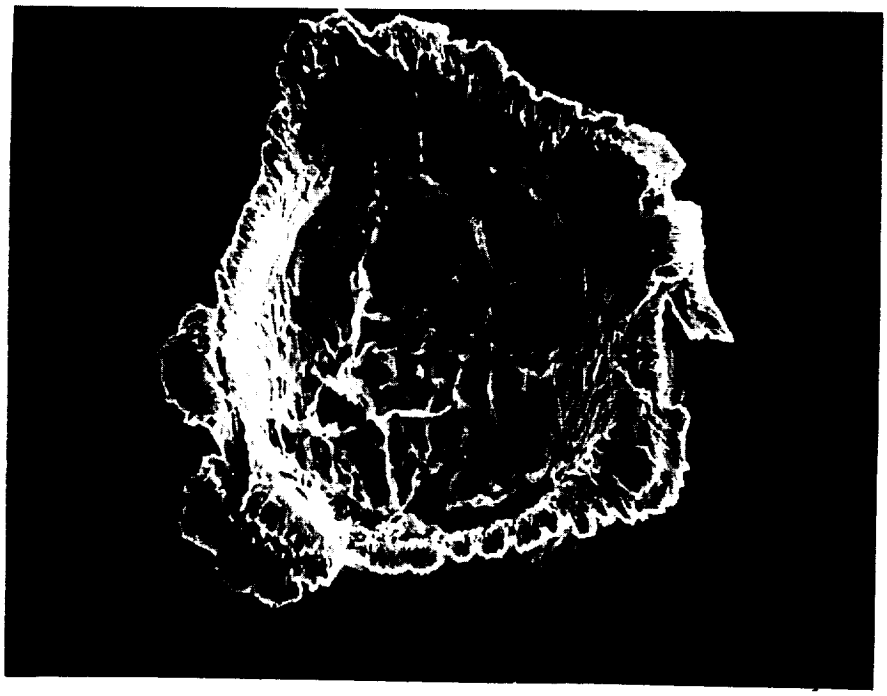
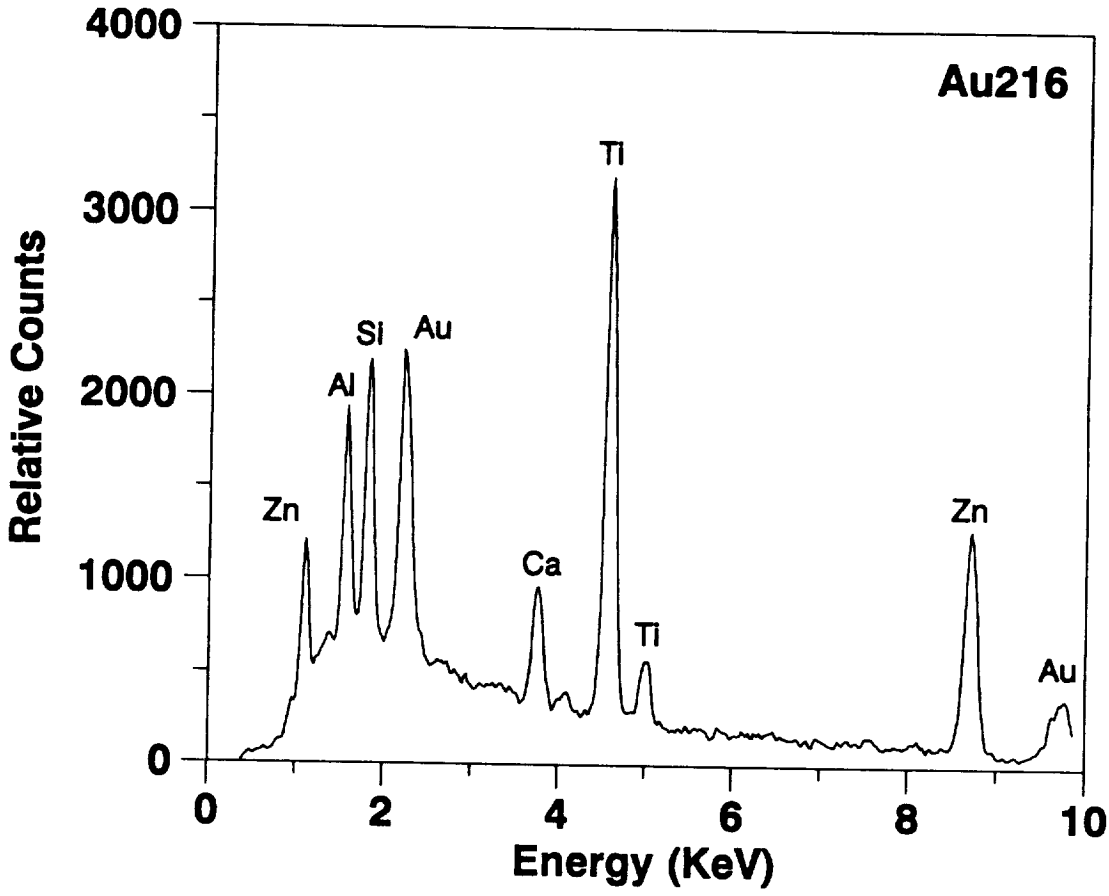


COMPONENT: EOOI
FEATURE: 216
CORE: LD-168

DIAMETER: 60 μm
ORIGIN: Man-made



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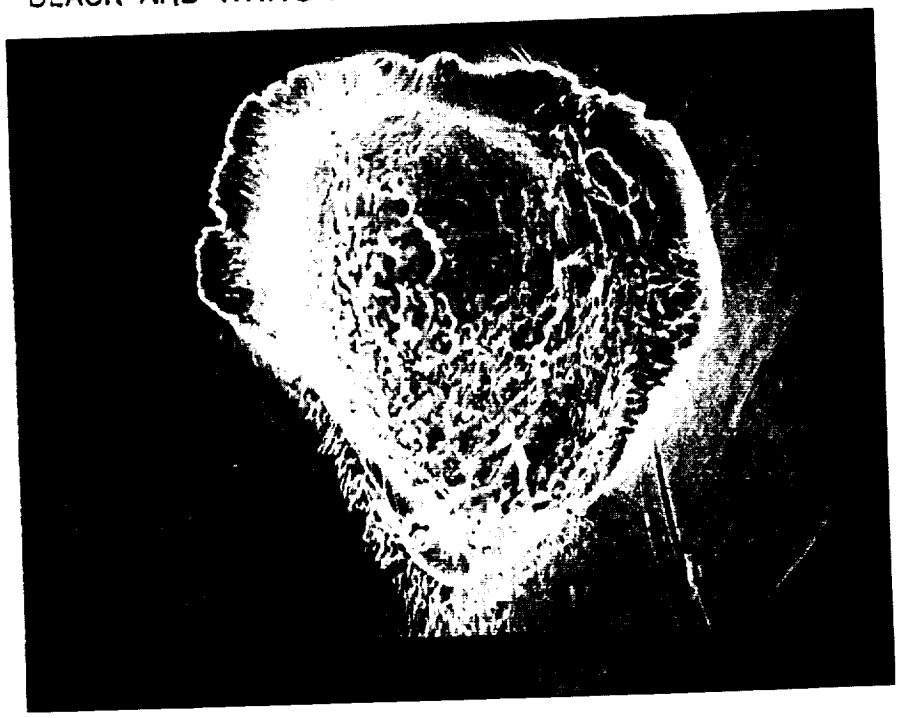
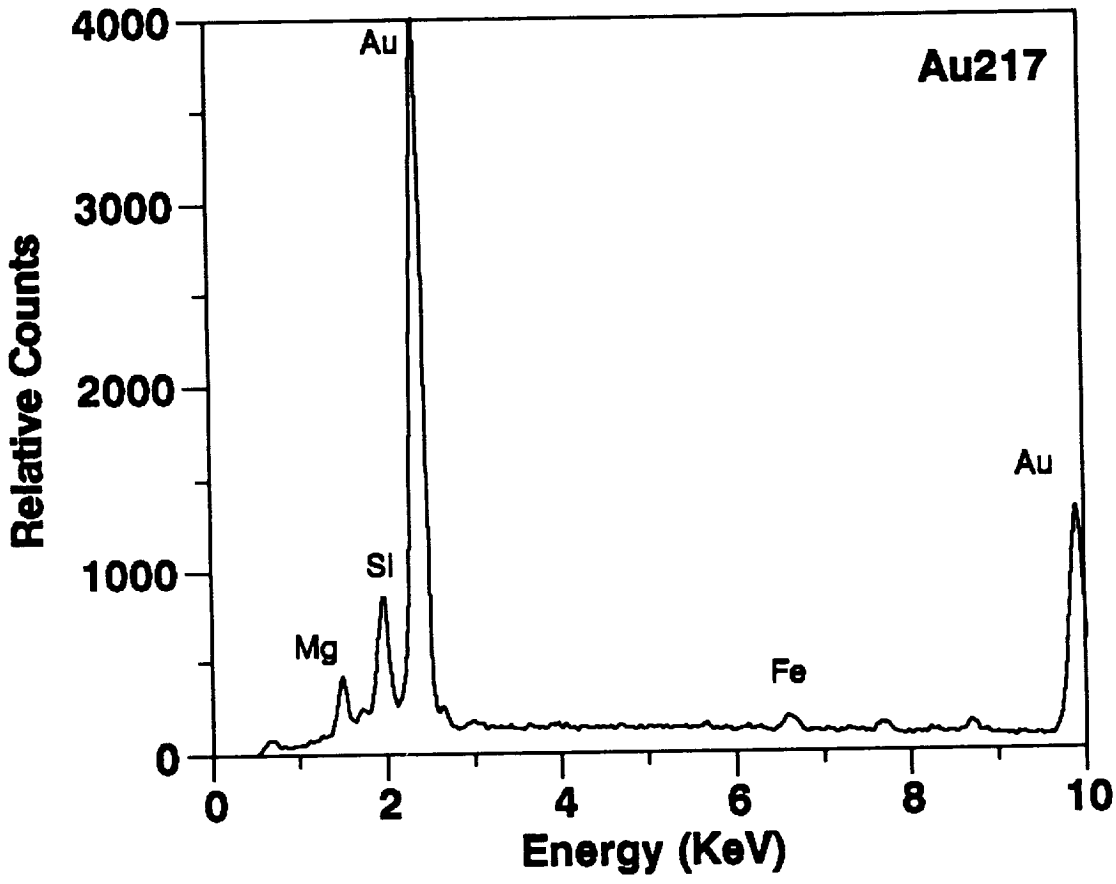


COMPONENT: EOOI
FEATURE: 217
CORE: LD-169

DIAMETER: 40 μm
ORIGIN: Natural



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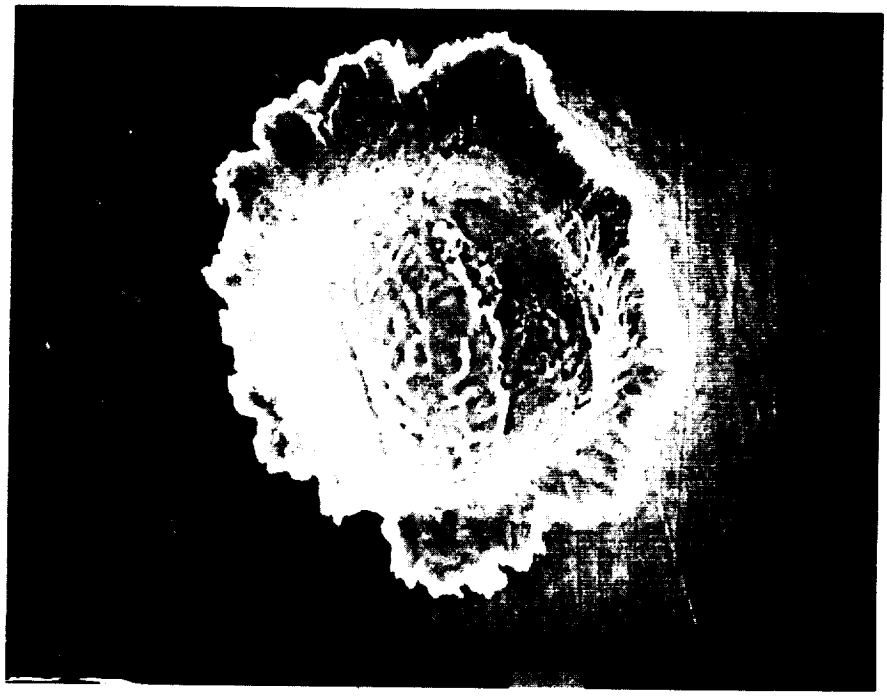
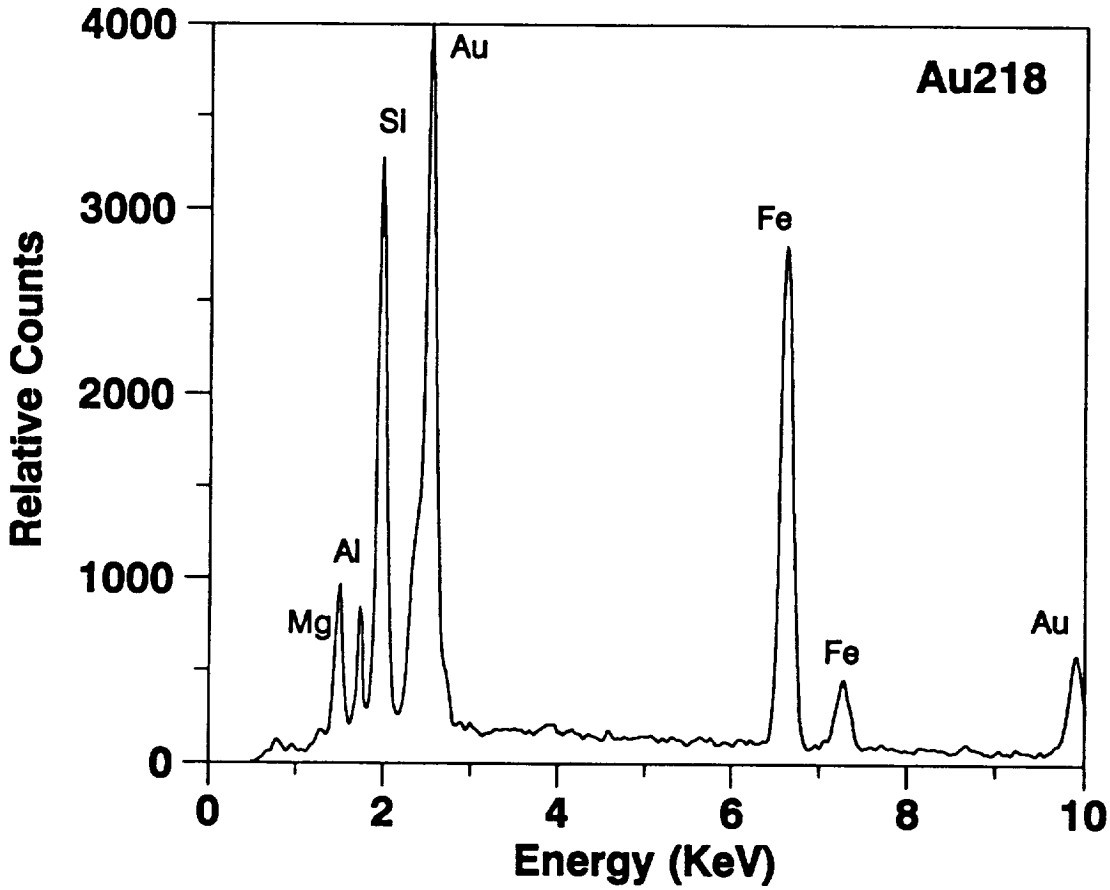


COMPONENT: EOOI
FEATURE: 218
CORE: LD-170

DIAMETER: 20 μm
ORIGIN: Natural



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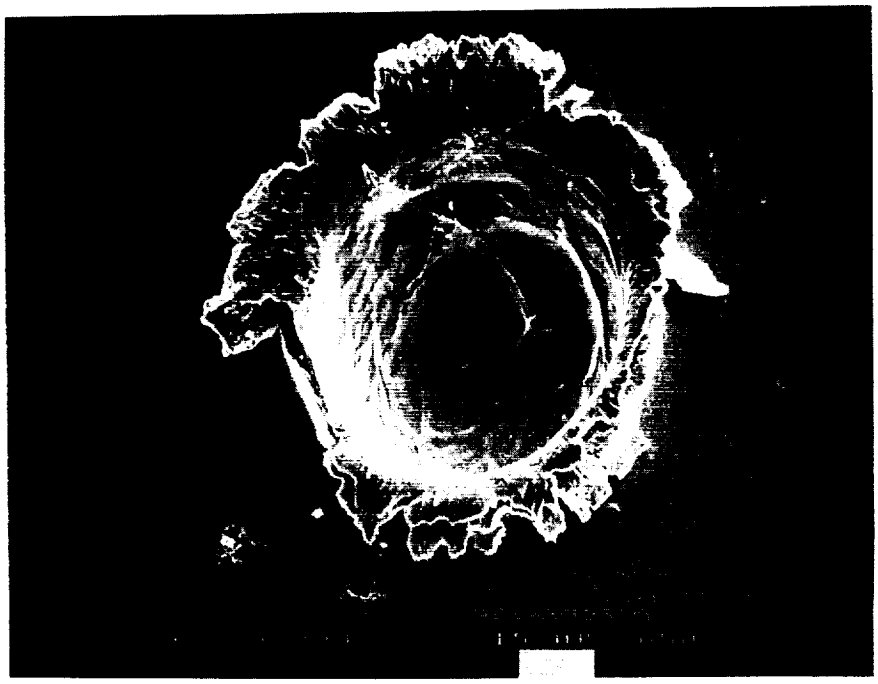
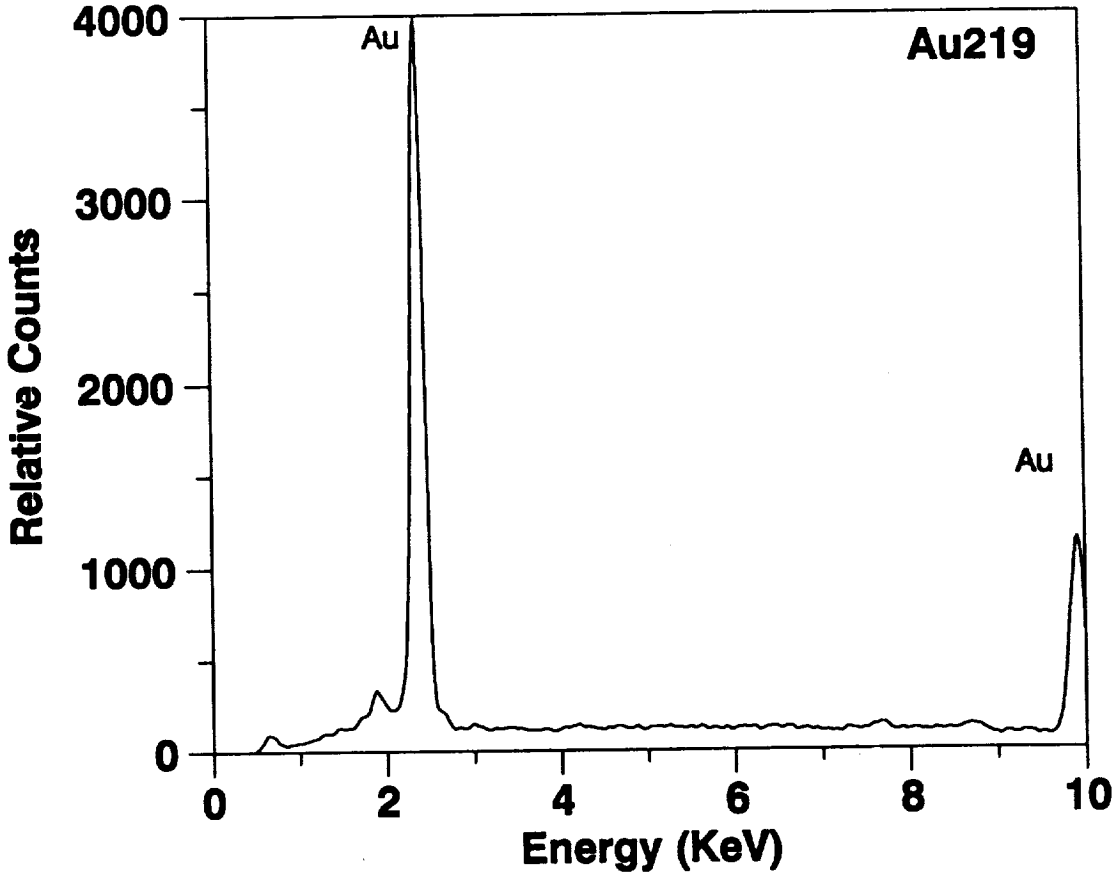


COMPONENT: E00I
FEATURE: 219
CORE: LD-195

DIAMETER: 70 μm
ORIGIN: Unknown



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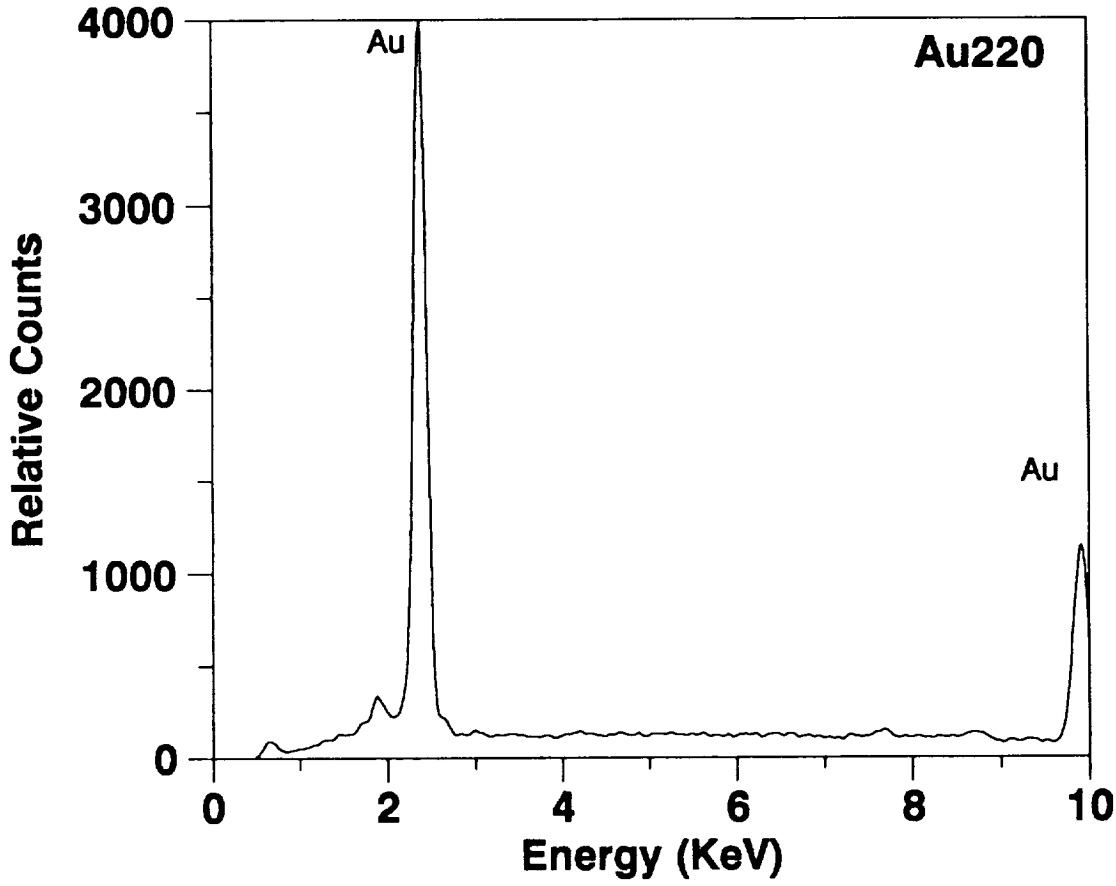
COMPONENT: EOOI
FEATURE: 220
CORE: LD-189

DIAMETER: 25 μm
ORIGIN: Unknown



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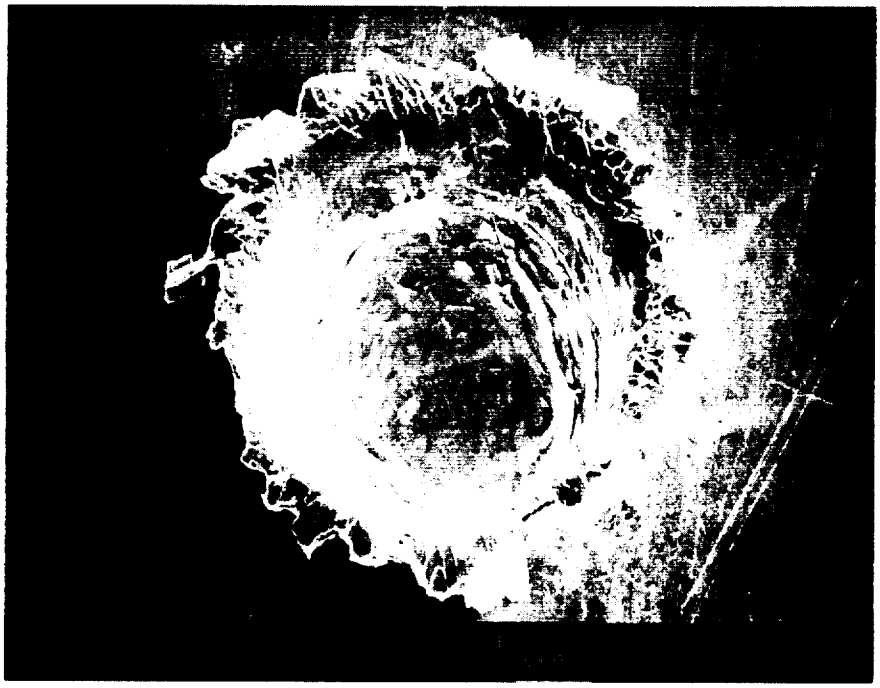
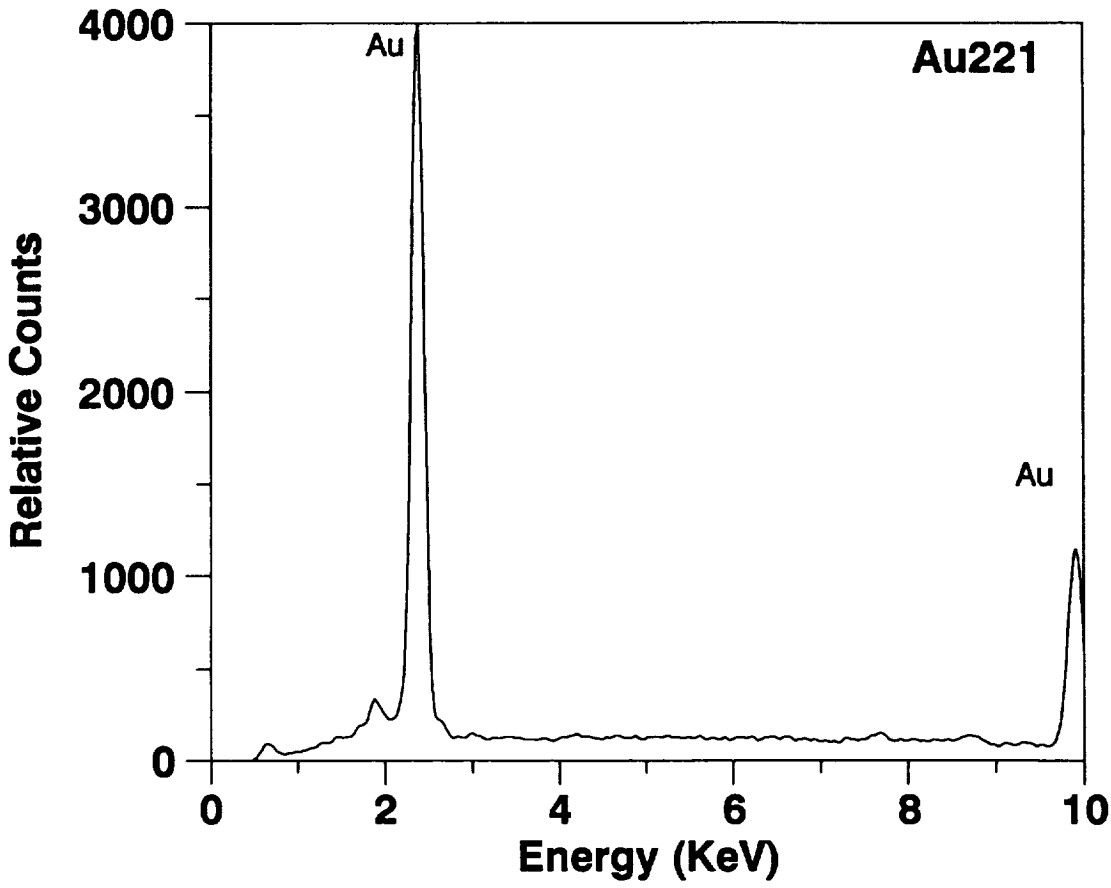


COMPONENT: EOOI
FEATURE: 221
CORE: LD-191

DIAMETER: 100 μm
ORIGIN: Unknown



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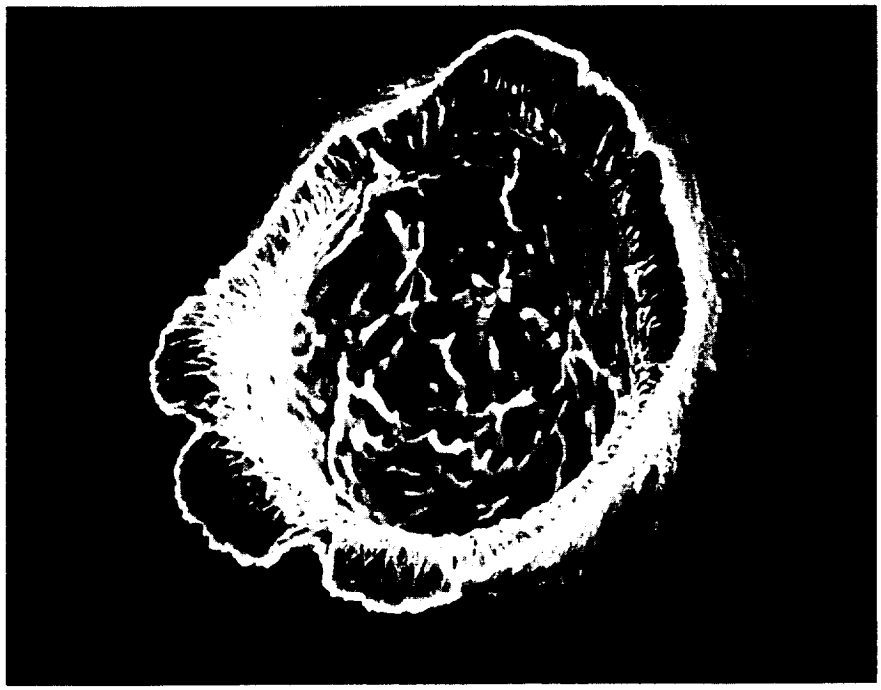
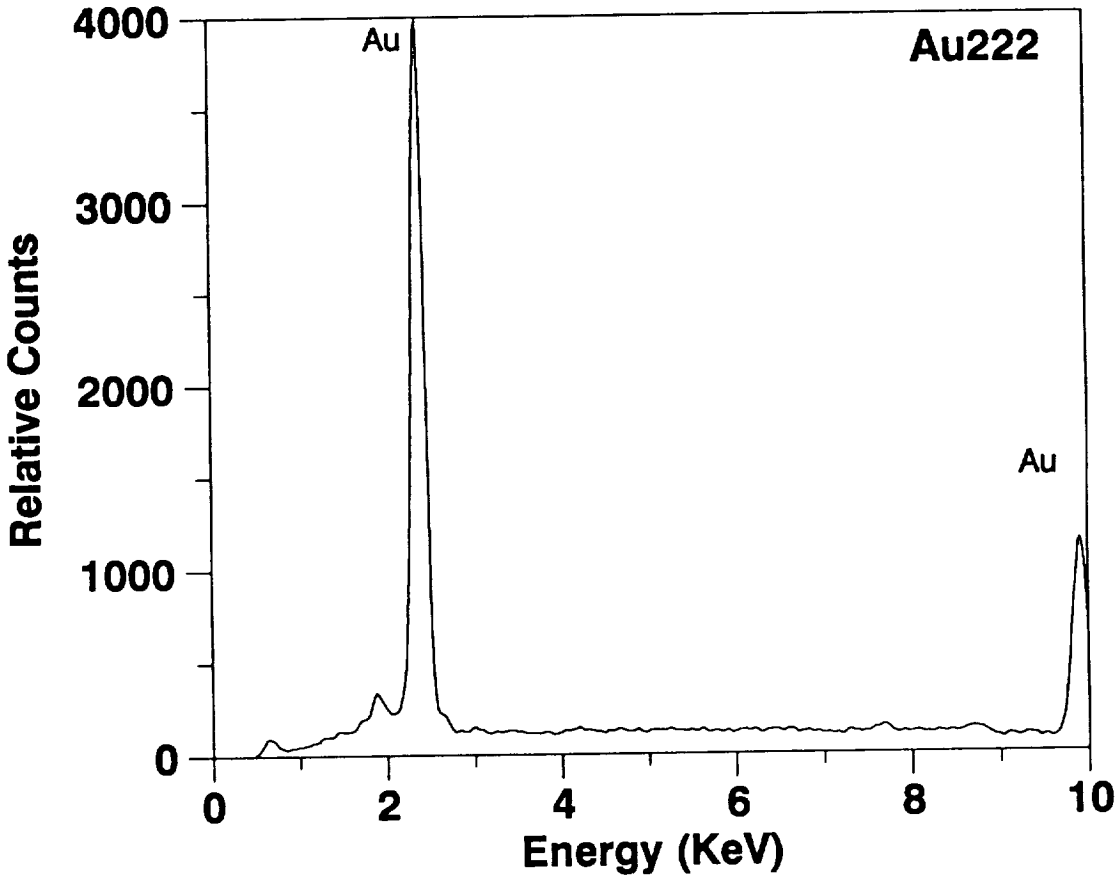


COMPONENT: EOOI
FEATURE: 222
CORE: LD-192

DIAMETER: 25 μm
ORIGIN: Unknown



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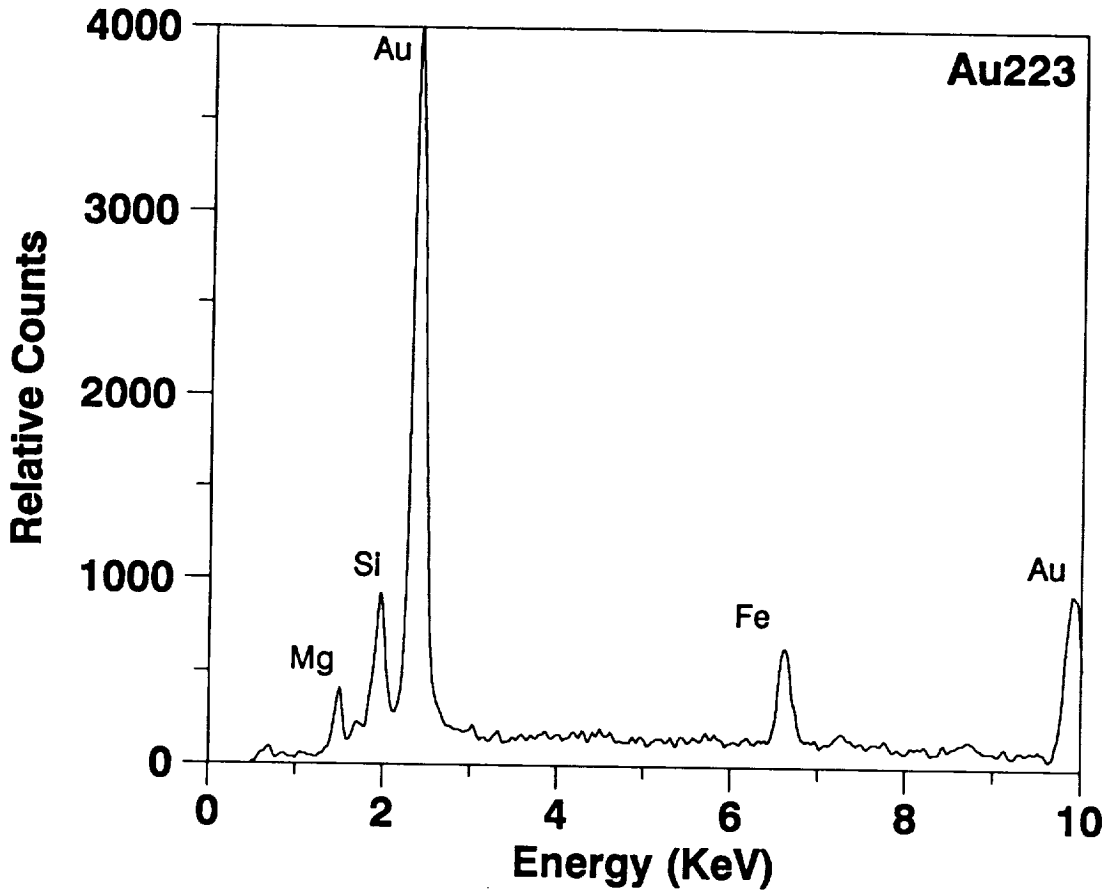
COMPONENT: EOOI
FEATURE: 223
CORE: LD-193

DIAMETER: 45 μm
ORIGIN: Natural



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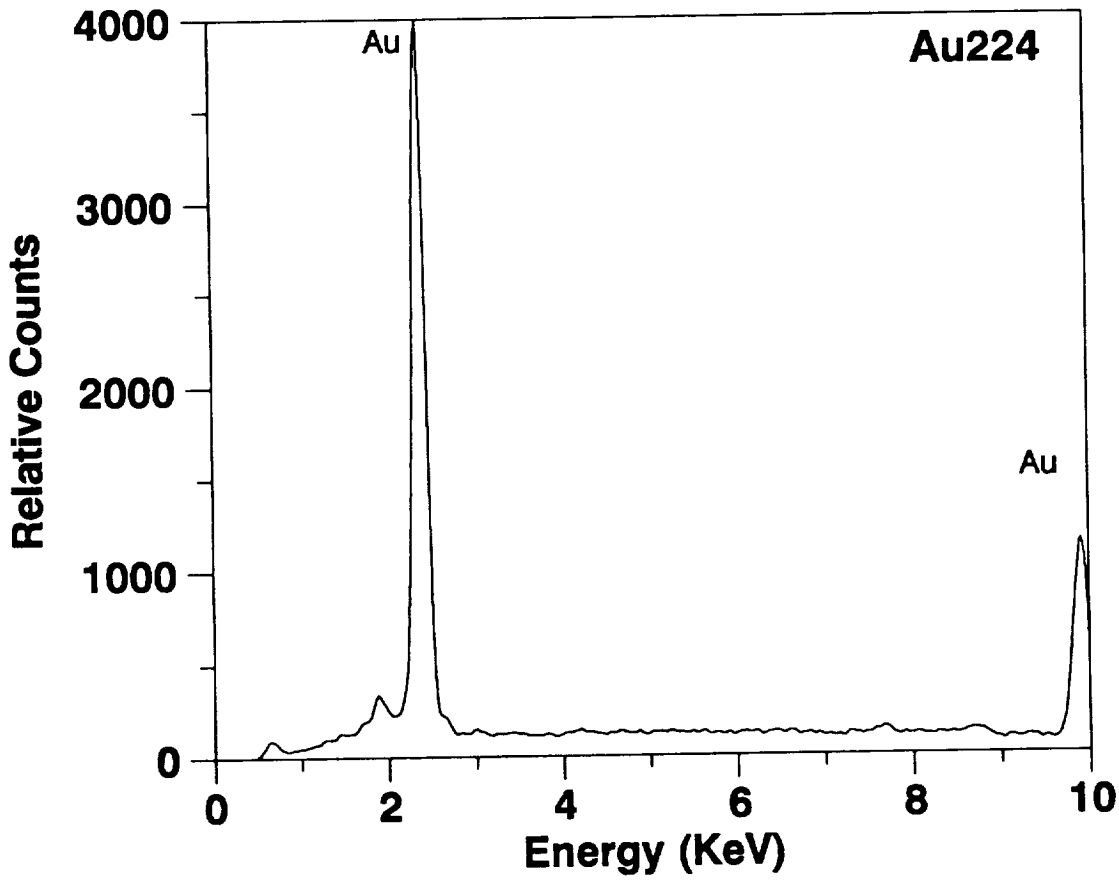
COMPONENT: EOOI
FEATURE: 224
CORE: LD-188

DIAMETER: 180 μm
ORIGIN: Unknown



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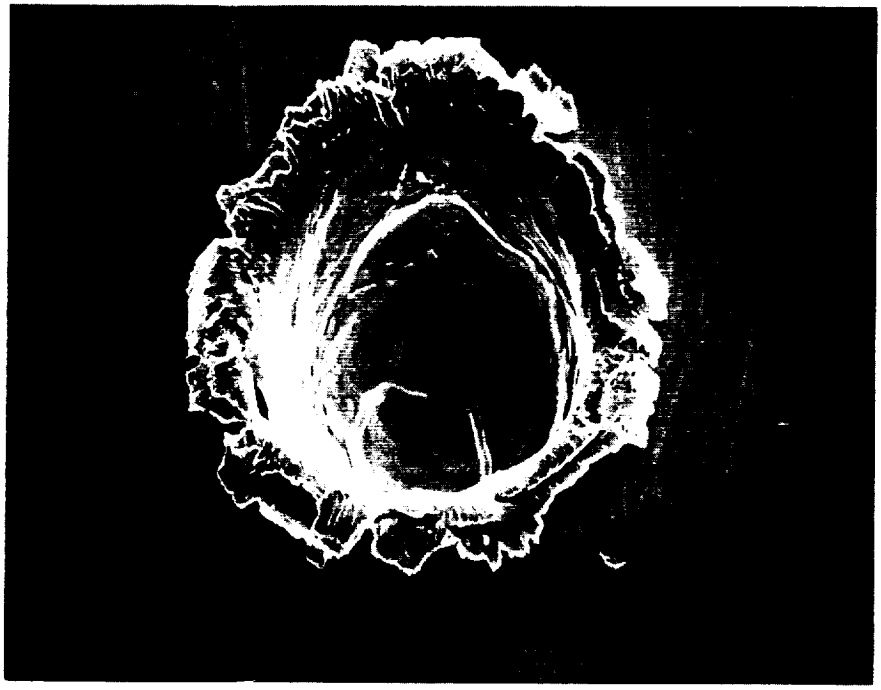
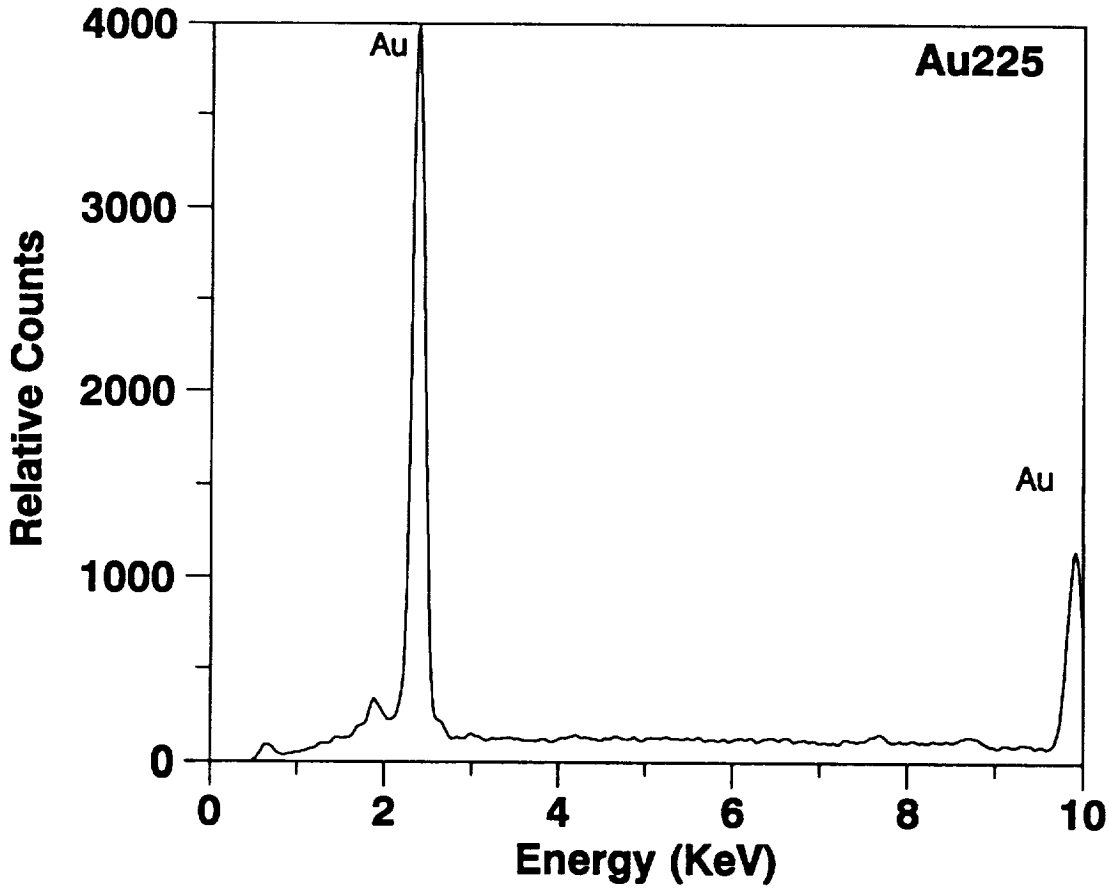


COMPONENT: EOOI
FEATURE: 225
CORE: LD-194

DIAMETER: 80 μm
ORIGIN: Unknown



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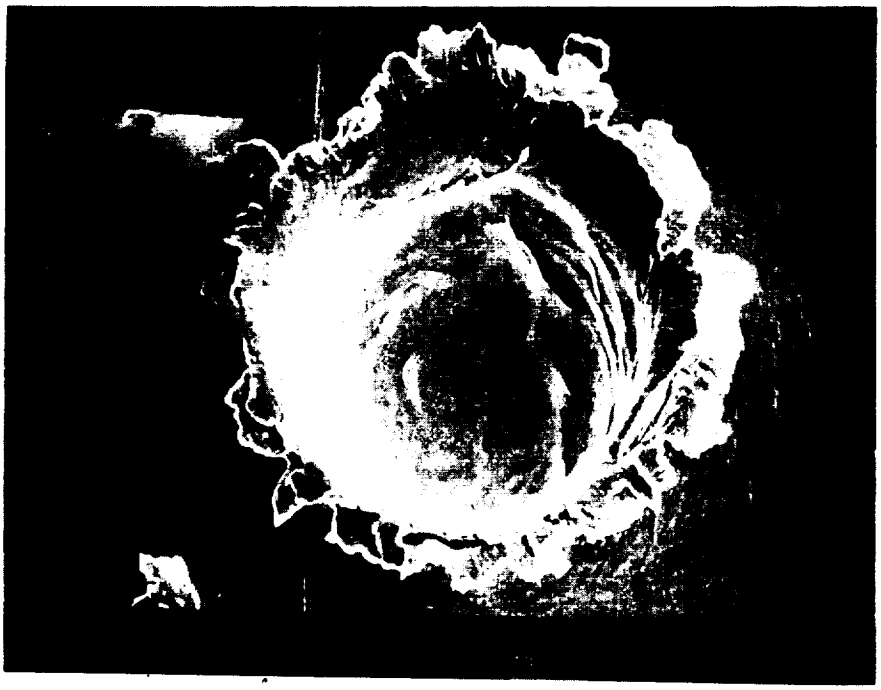
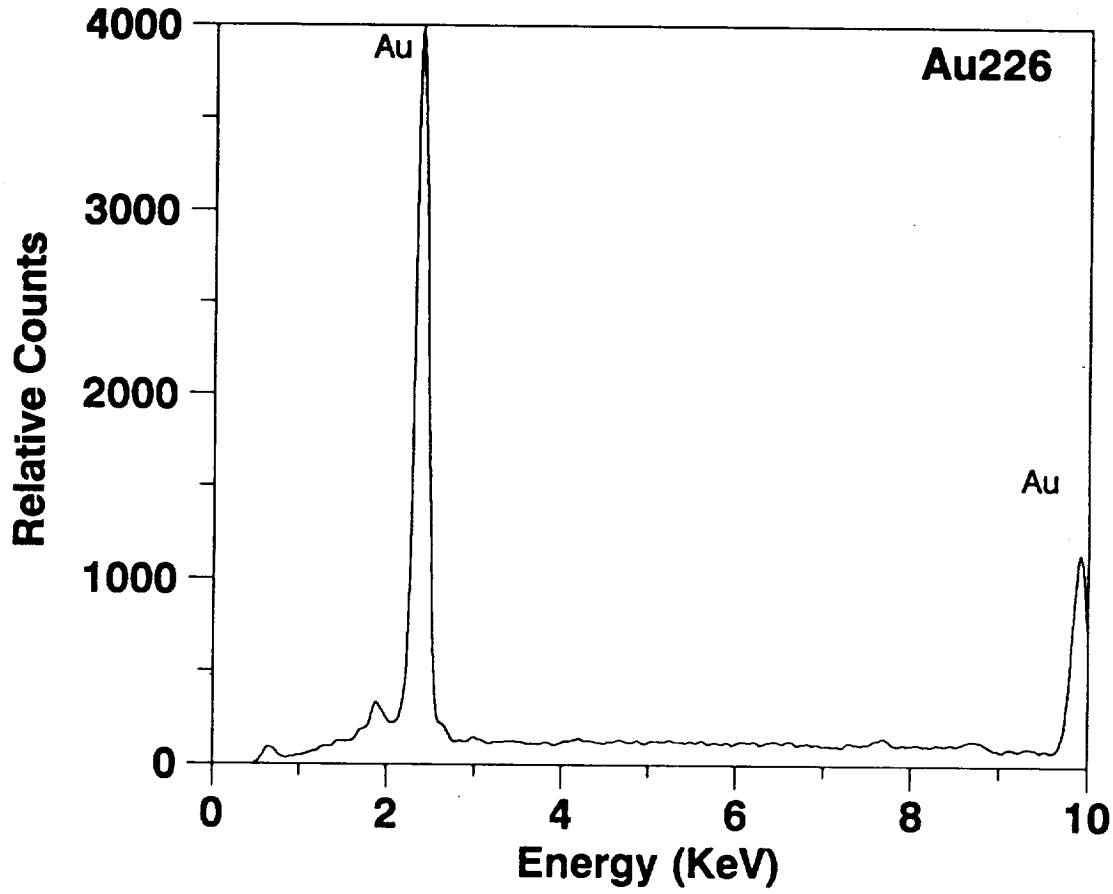


COMPONENT: EOOI
FEATURE: 226
CORE: LD-190

DIAMETER: 60 μm
ORIGIN: Unknown



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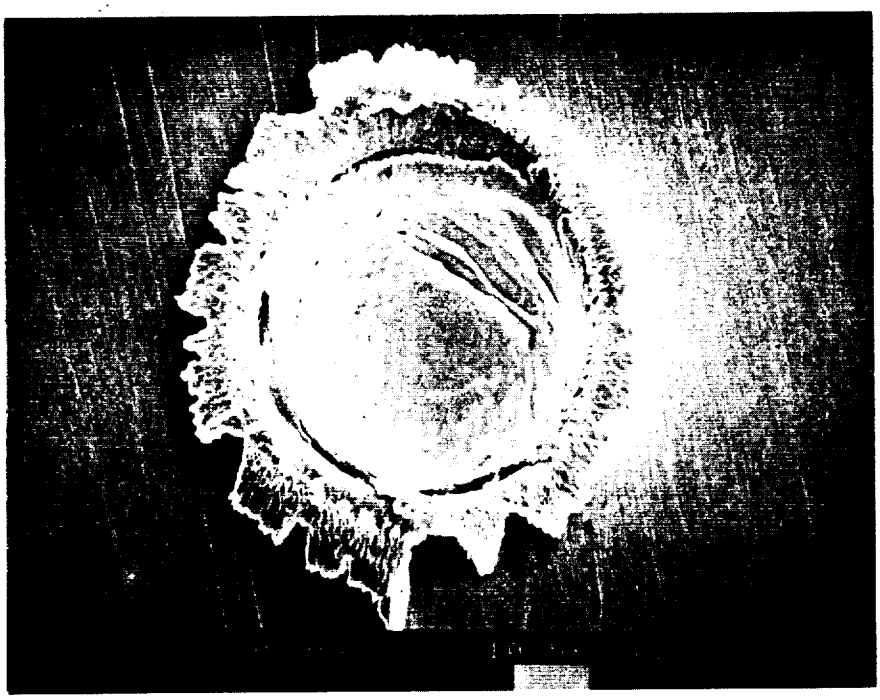
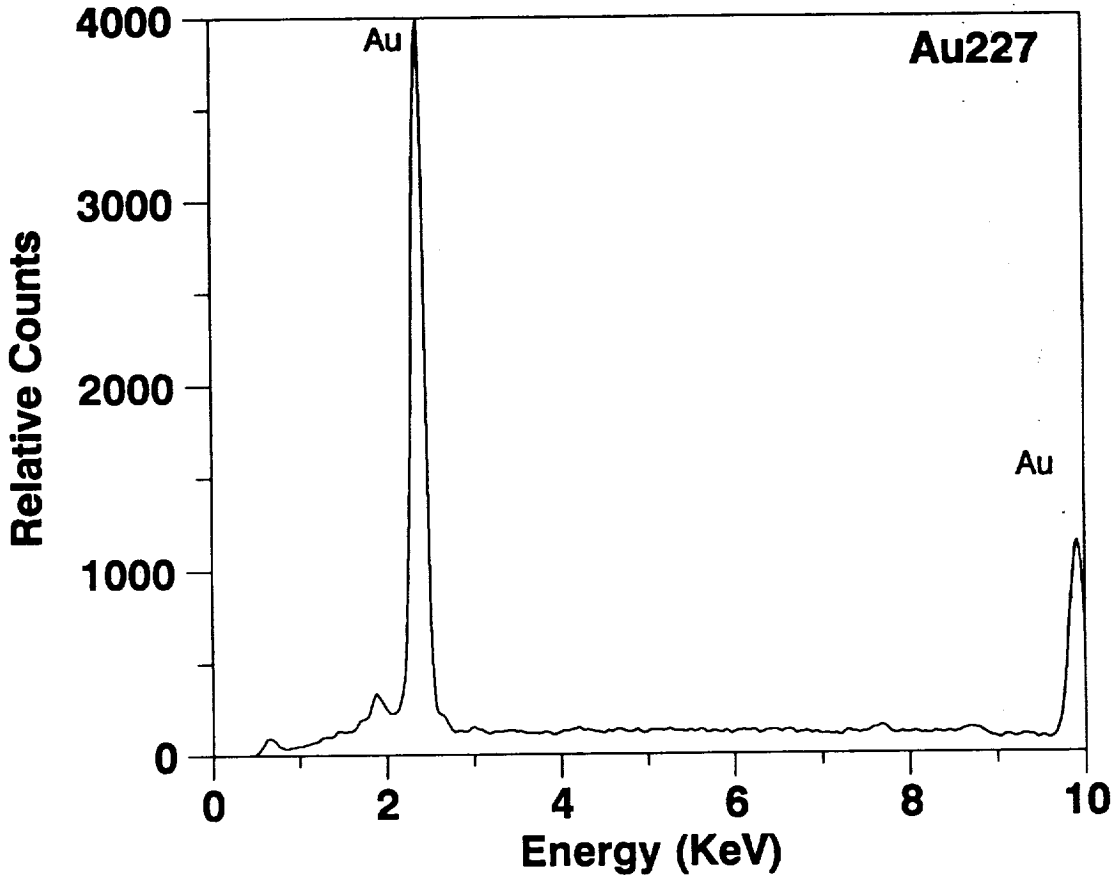


COMPONENT: EOOI
FEATURE: 227
CORE: LD-171

DIAMETER: 50 μm
ORIGIN: Unknown



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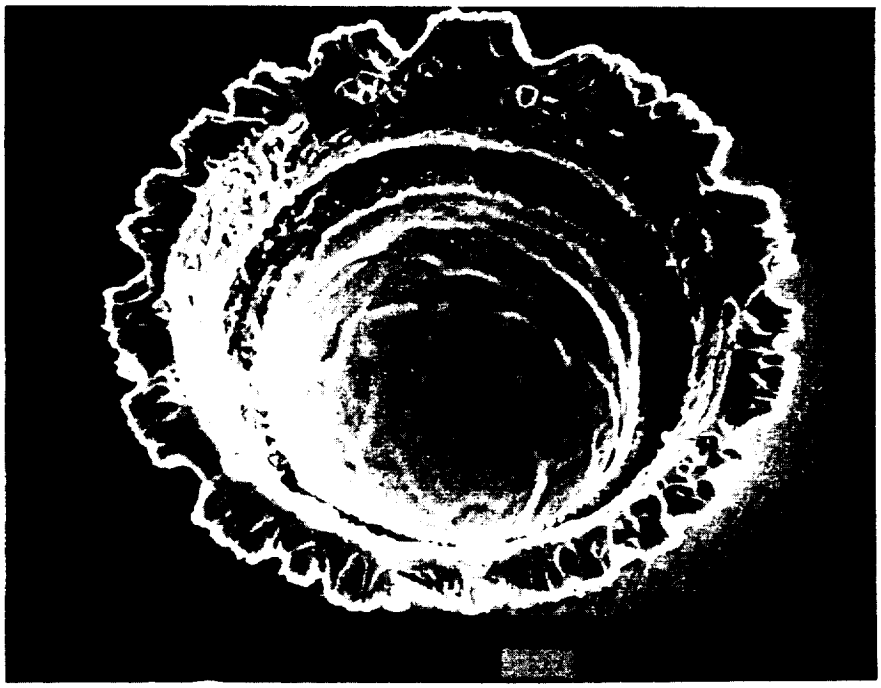
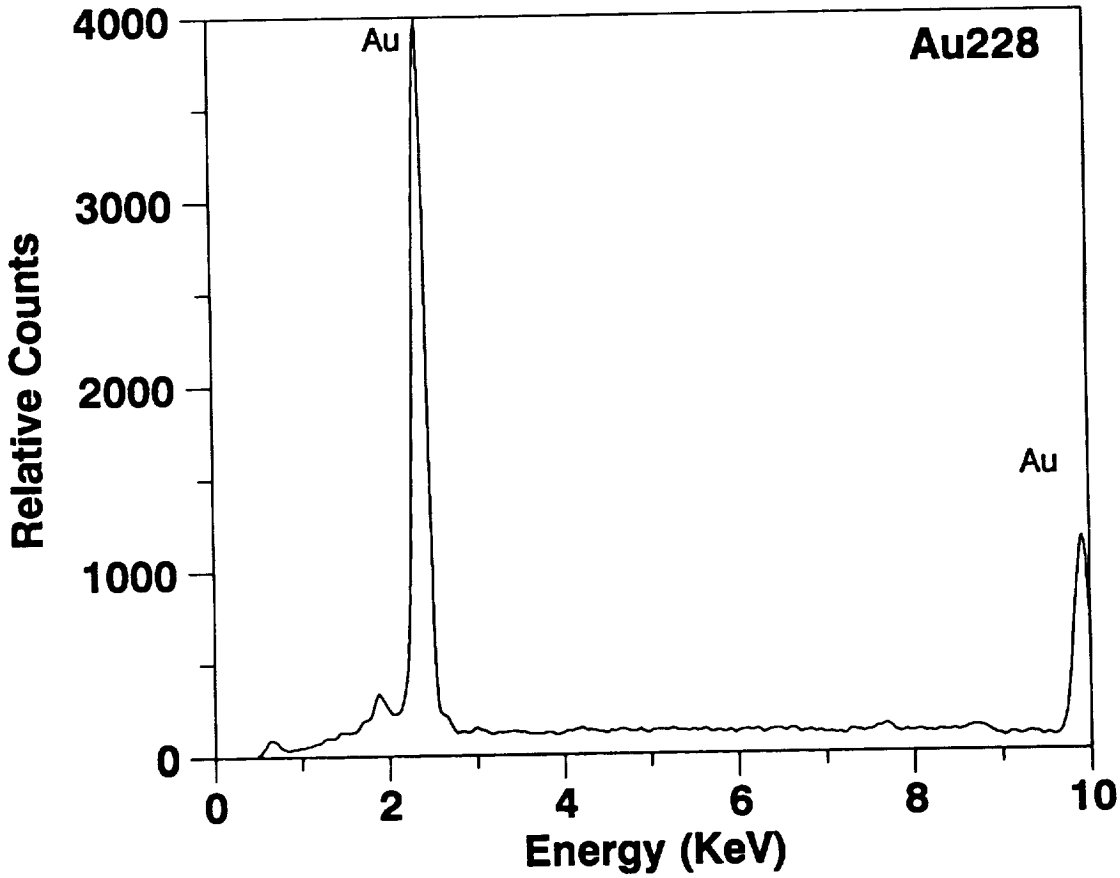


COMPONENT: EOOI
FEATURE: 228
CORE: LD-178

DIAMETER: 50 μm
ORIGIN: Unknown



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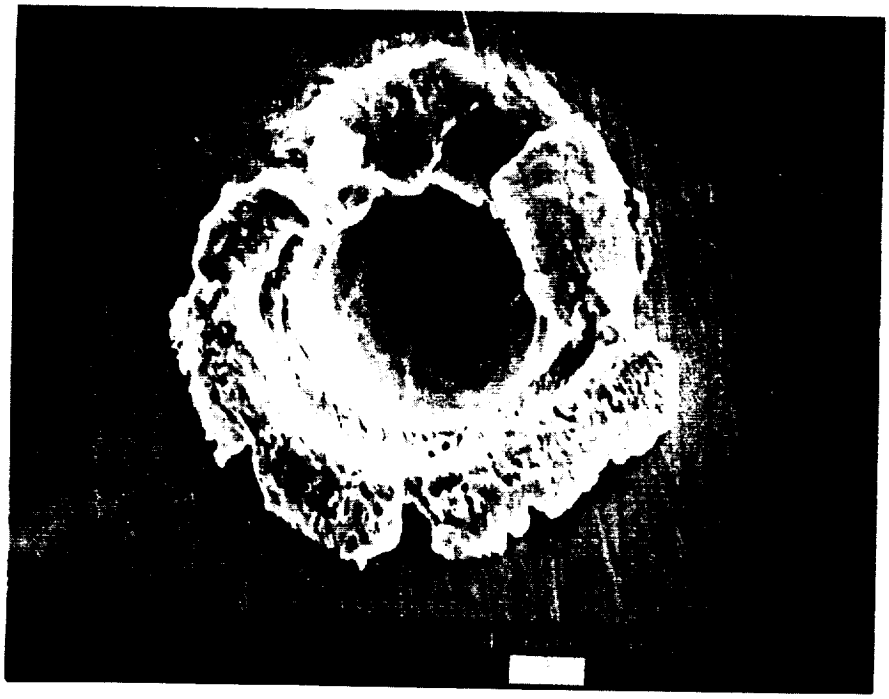
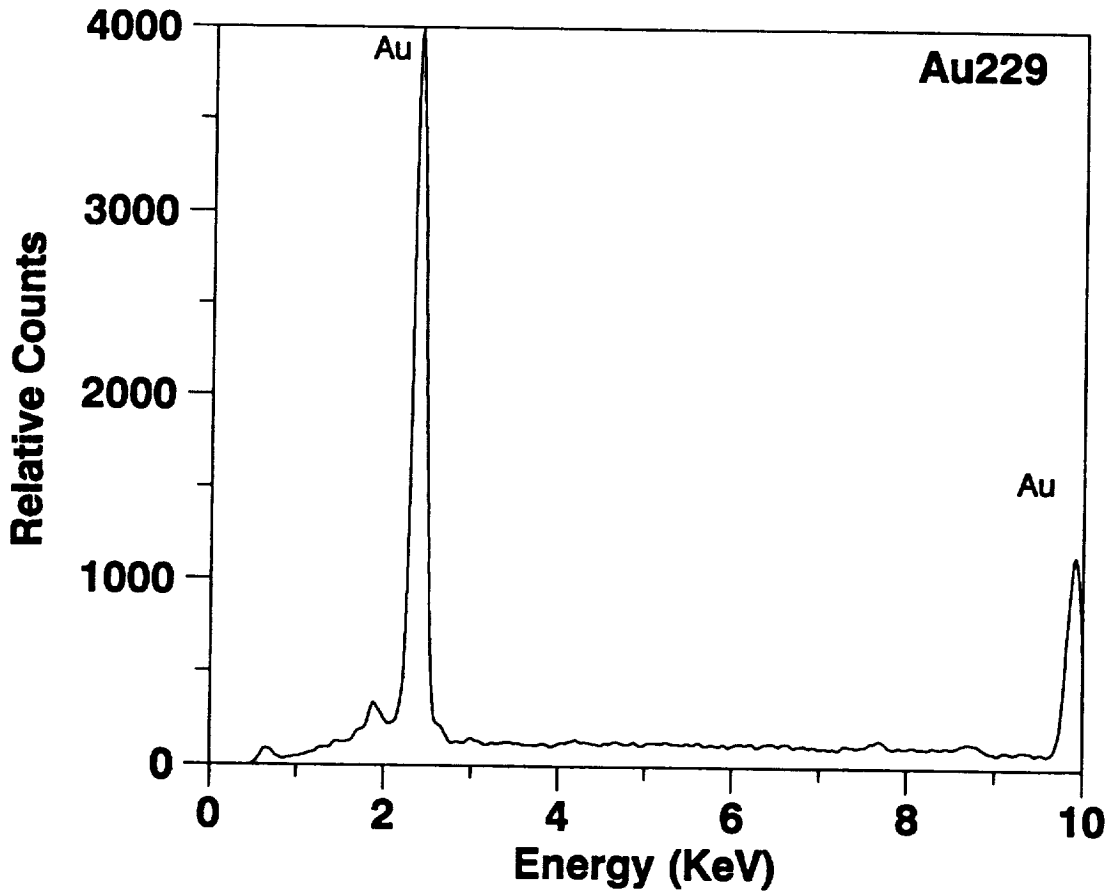


COMPONENT: EOOI
FEATURE: 229
CORE: LD-179

DIAMETER: 15 μm
ORIGIN: Unknown



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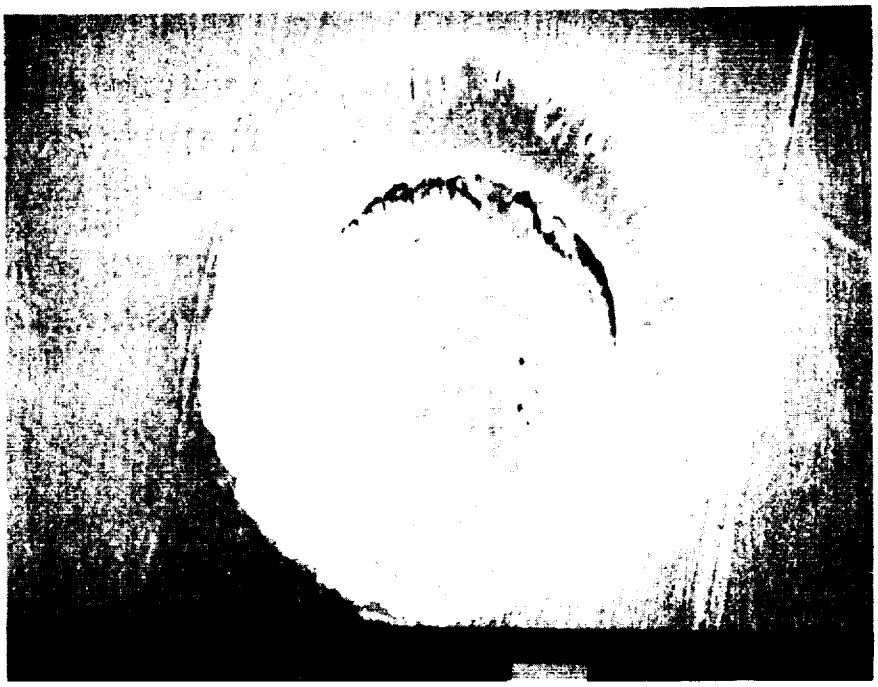
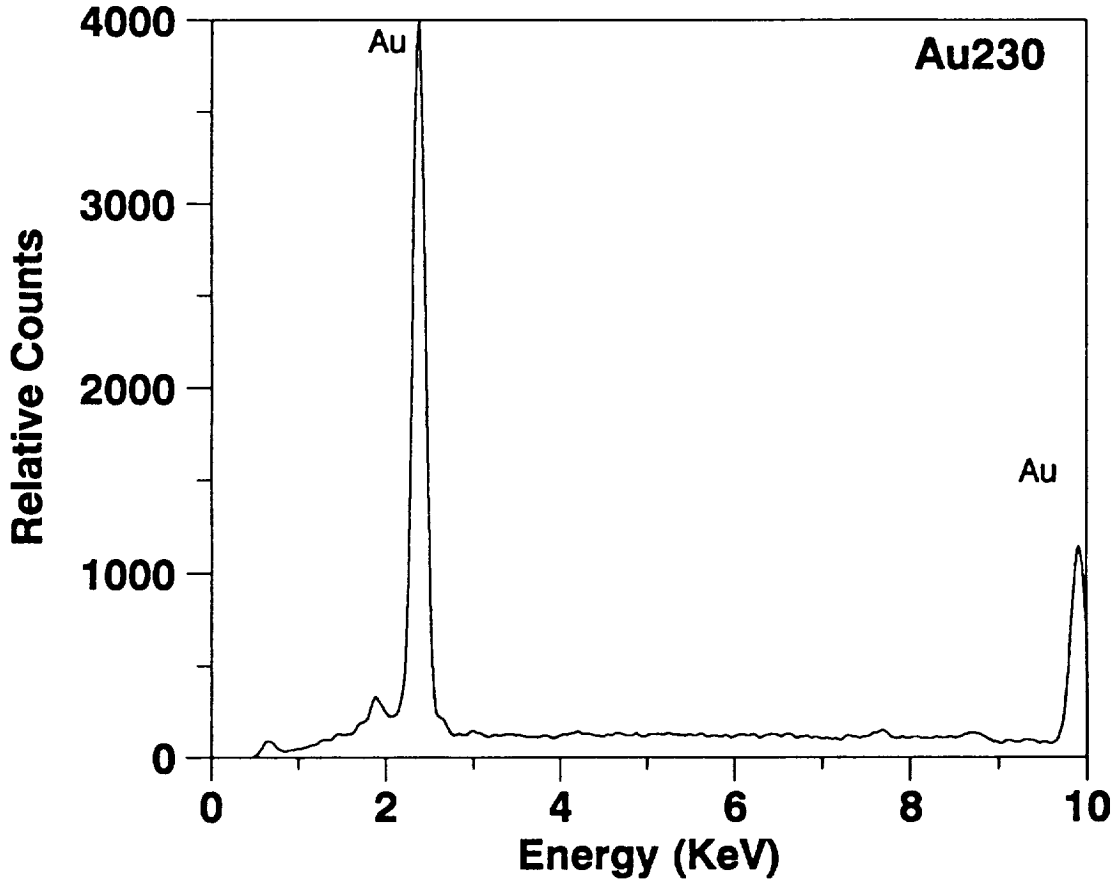


COMPONENT: EOOI
FEATURE: 230
CORE: LD-172

DIAMETER: 20 μm
ORIGIN: Unknown



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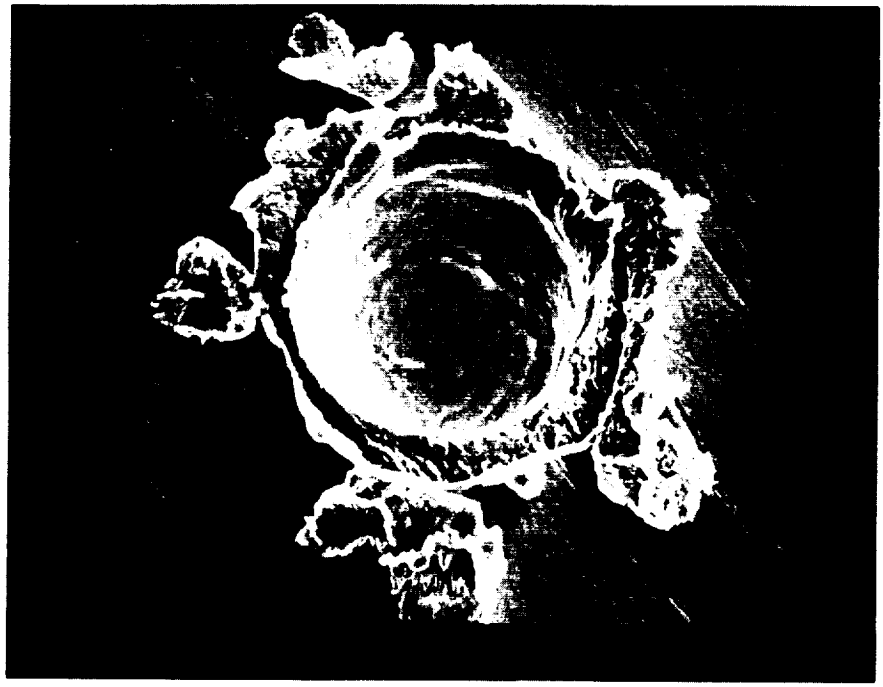
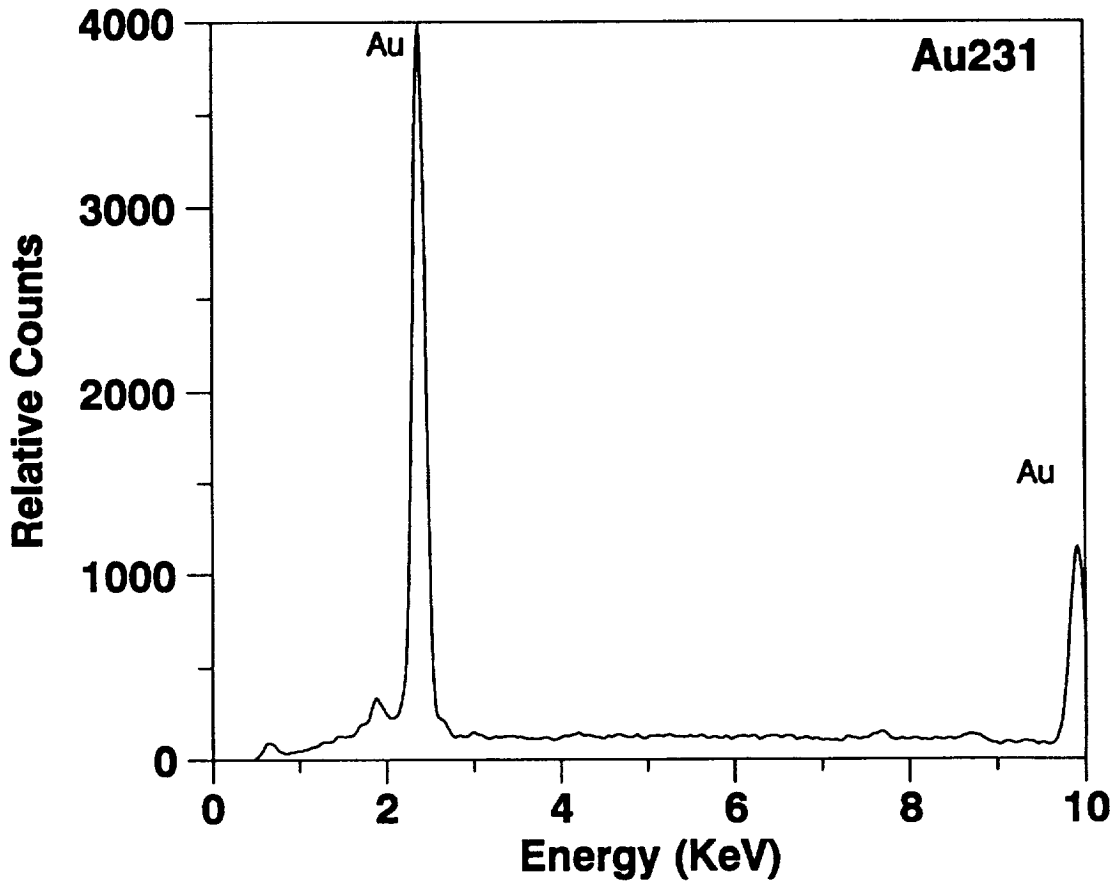


COMPONENT: EOOI
FEATURE: 231
CORE: LD-181

DIAMETER: 20 μm
ORIGIN: Unknown



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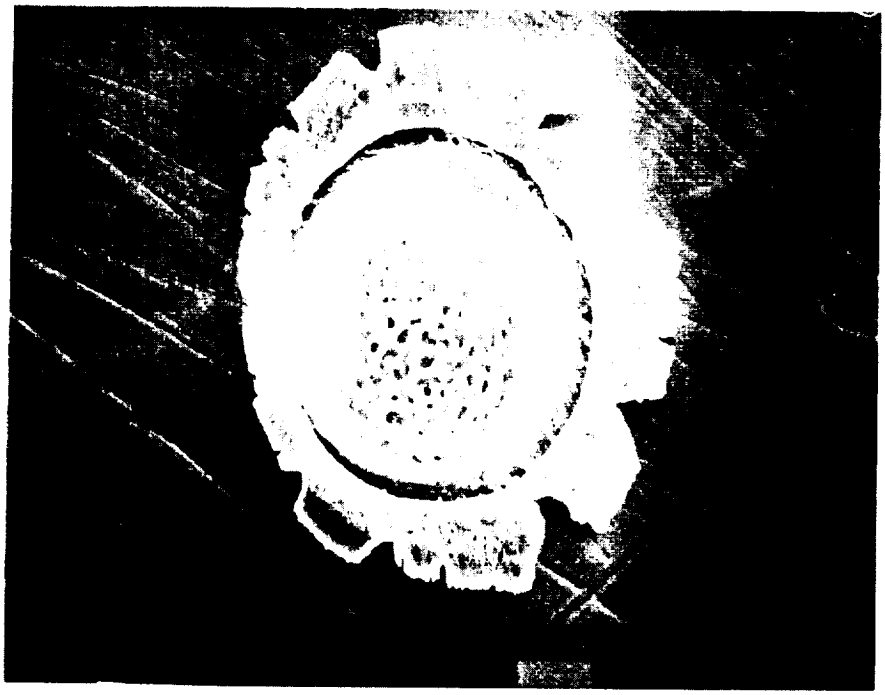
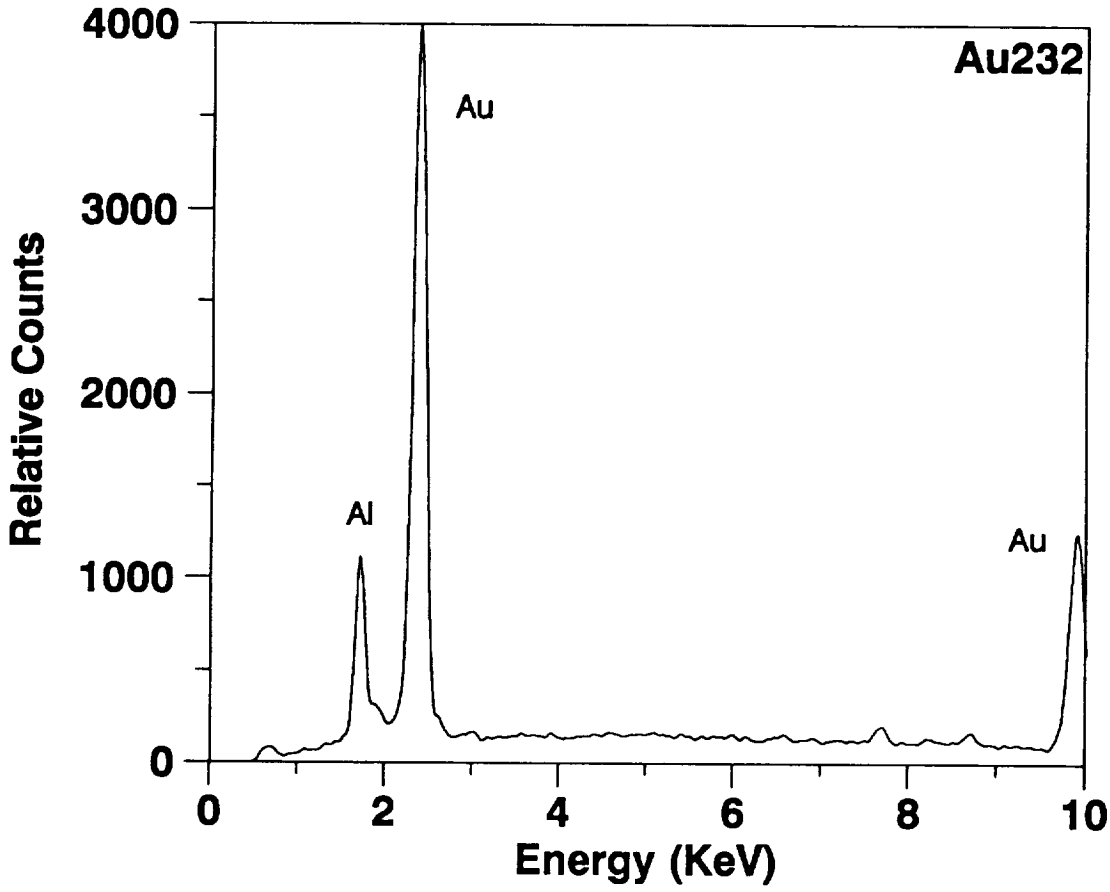


COMPONENT: EOOI
FEATURE: 232
CORE: LD-181

DIAMETER: 20 μm
ORIGIN: Man-made



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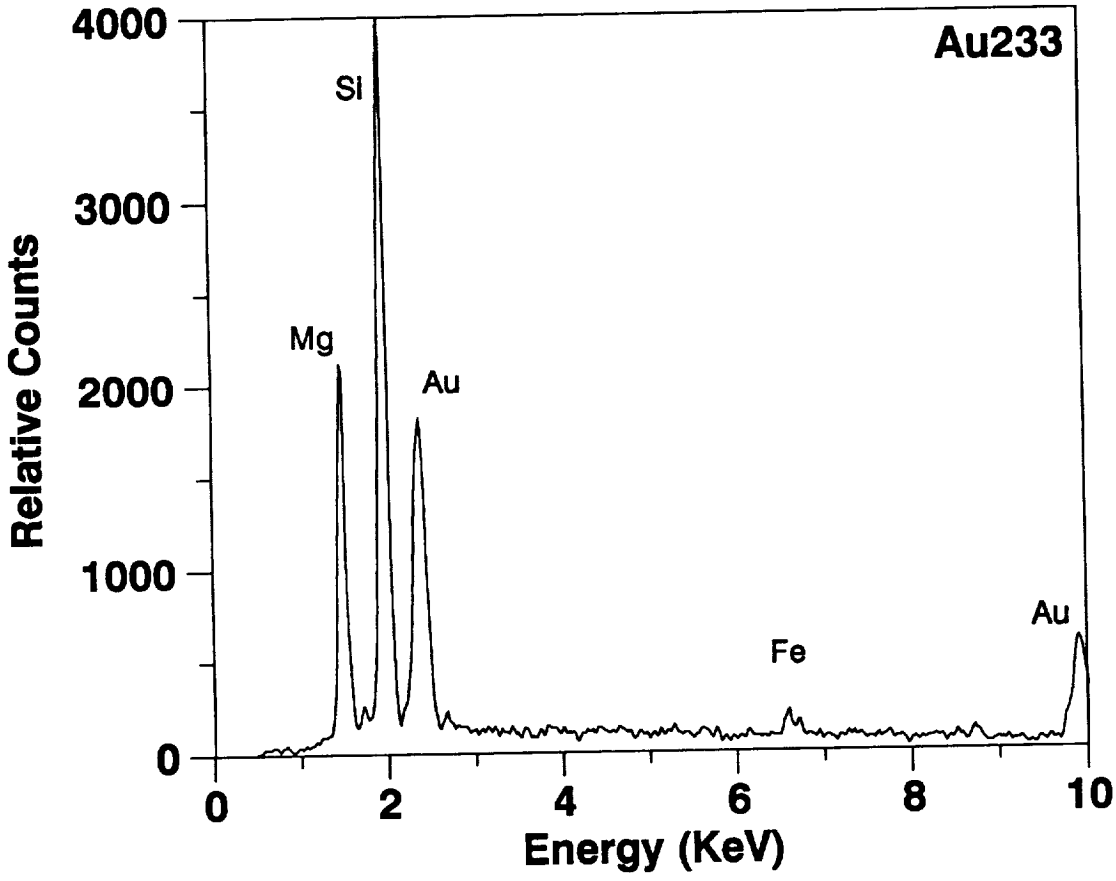
COMPONENT: EOOI
FEATURE: 233
CORE: LD-180

DIAMETER: 75 μm
ORIGIN: Natural



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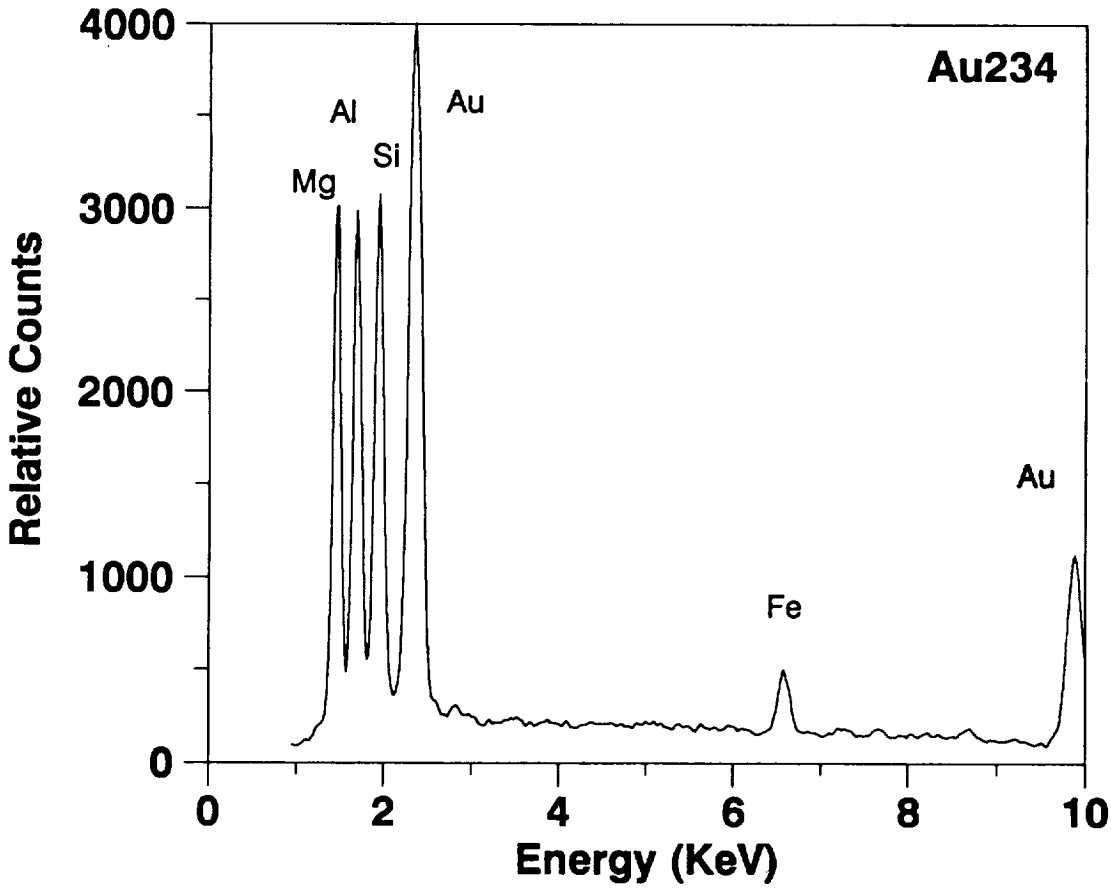
COMPONENT: EOOI
FEATURE: 234
CORE: LD-187

DIAMETER: 20 μm
ORIGIN: Natural



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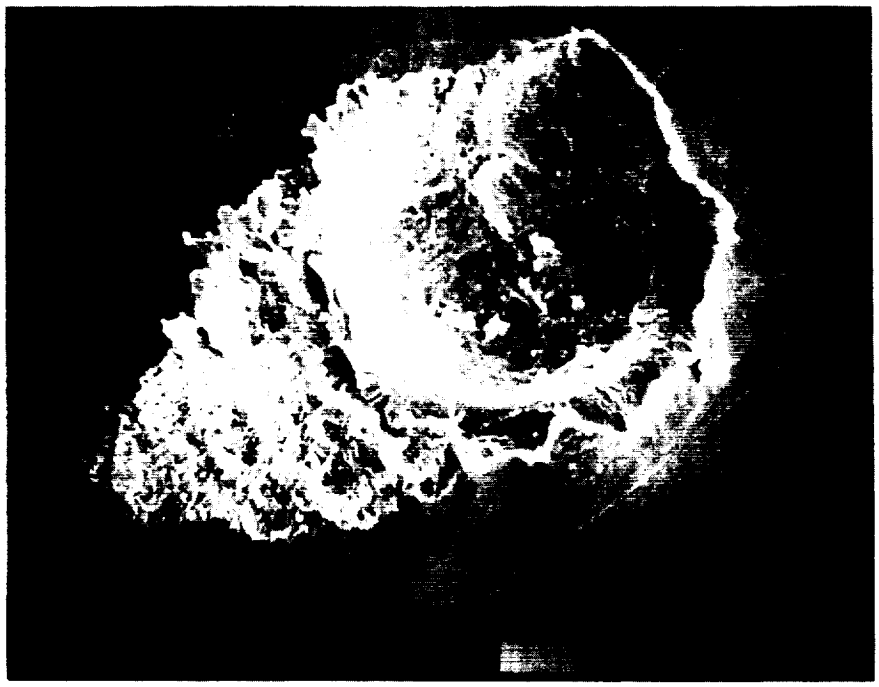
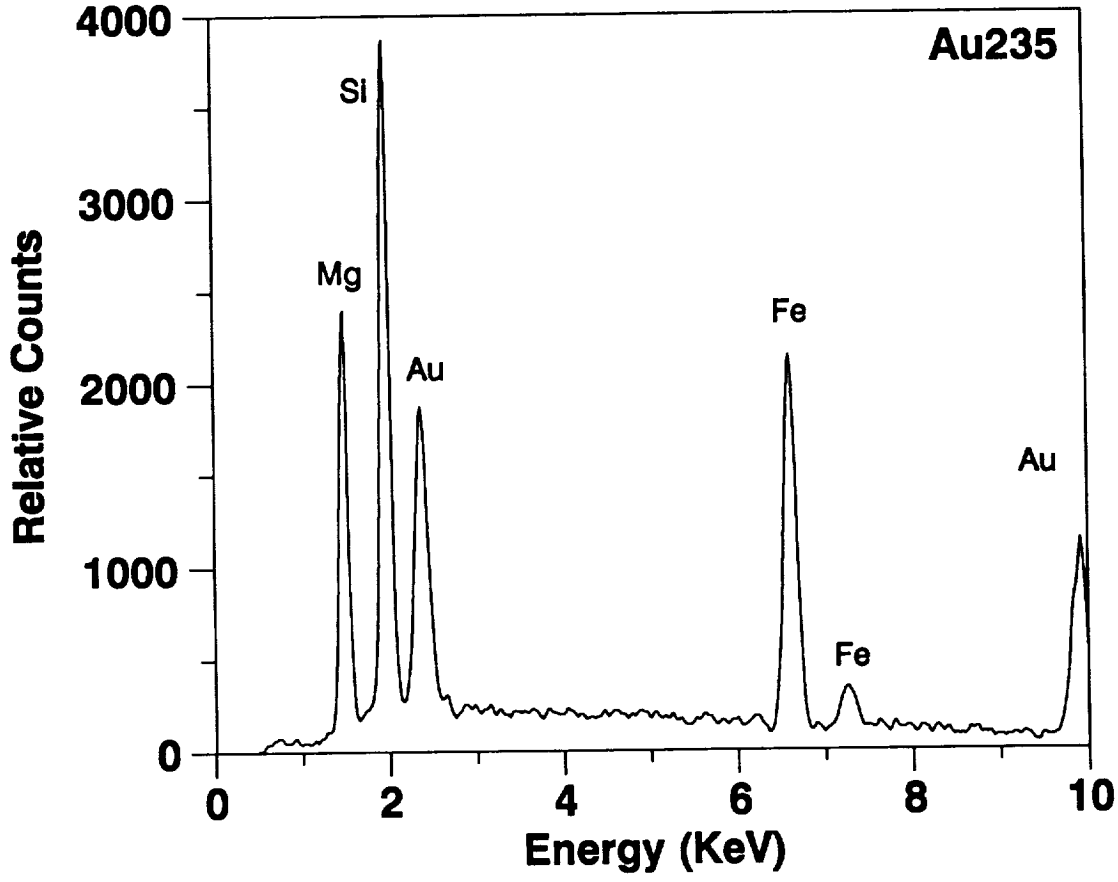


COMPONENT: EOOI
FEATURE: 235
CORE: LD-177

DIAMETER: 40 μm
ORIGIN: Natural



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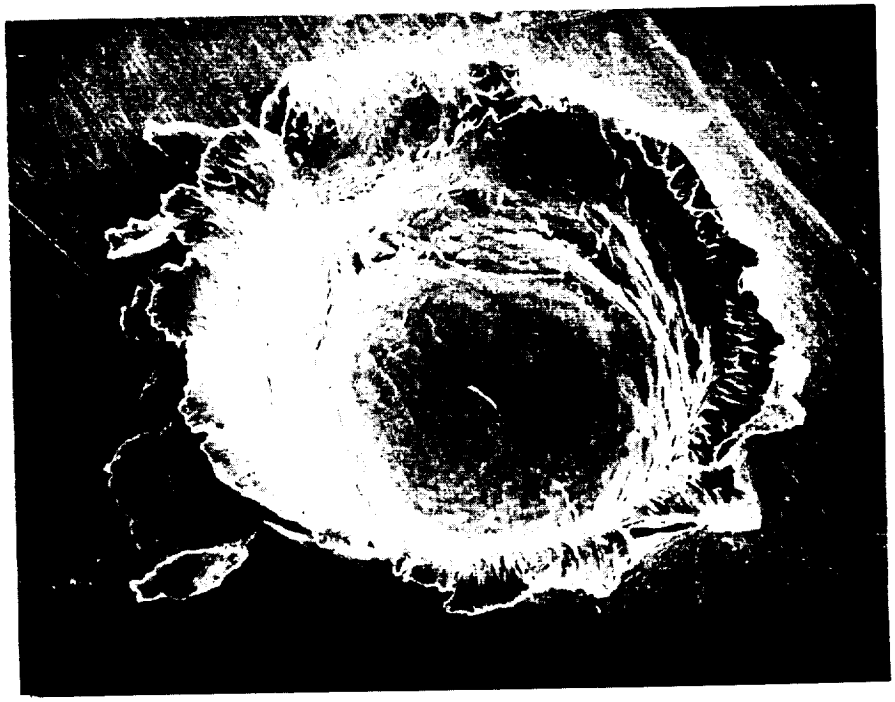
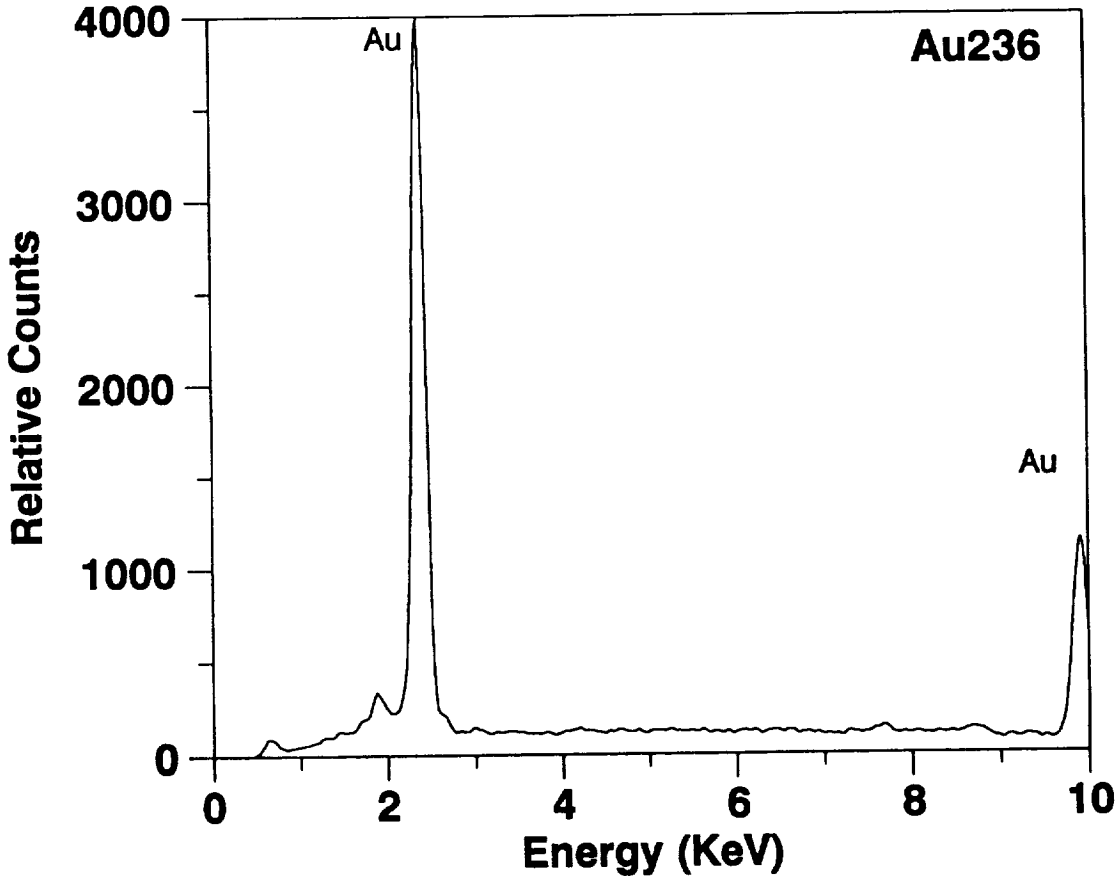


COMPONENT: EOOI
FEATURE: 236
CORE: LD-176

DIAMETER: 130 μm
ORIGIN: Unknown



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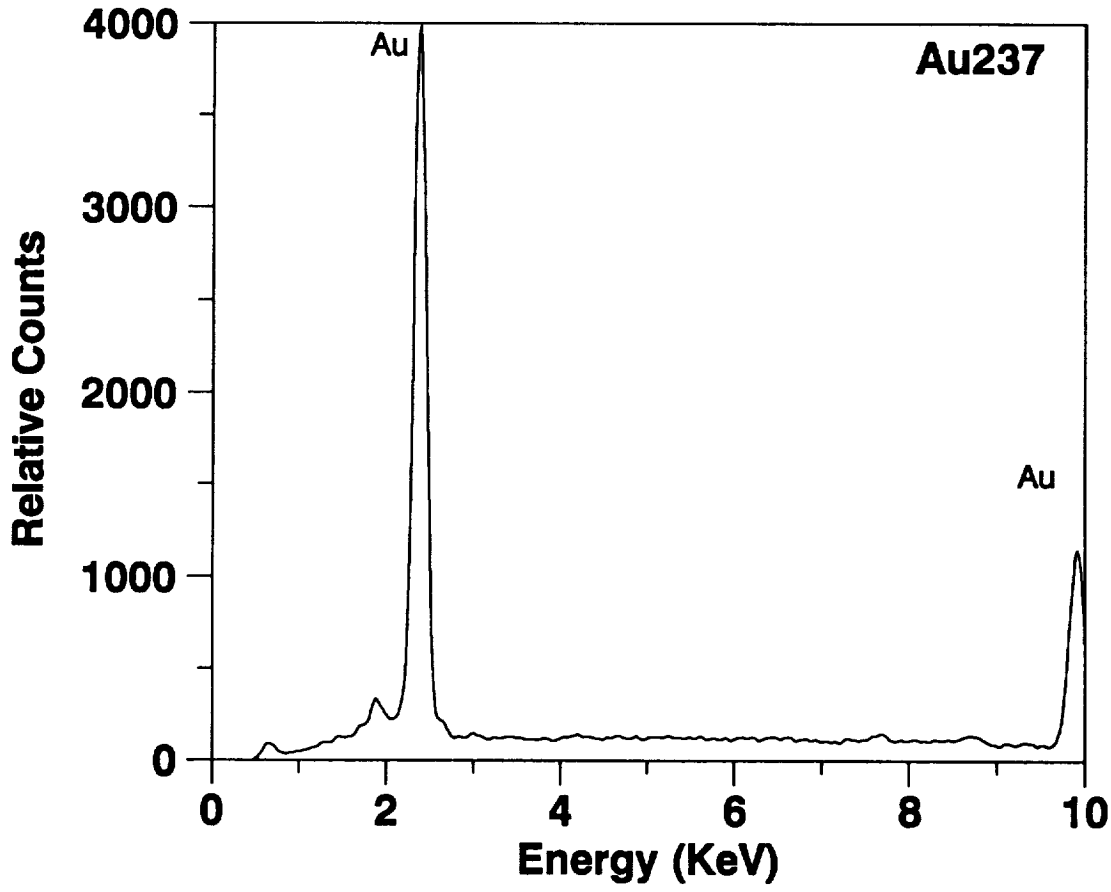
COMPONENT: EOOI
FEATURE: 237
CORE: LD-176

DIAMETER: 35 μm
ORIGIN: Unknown



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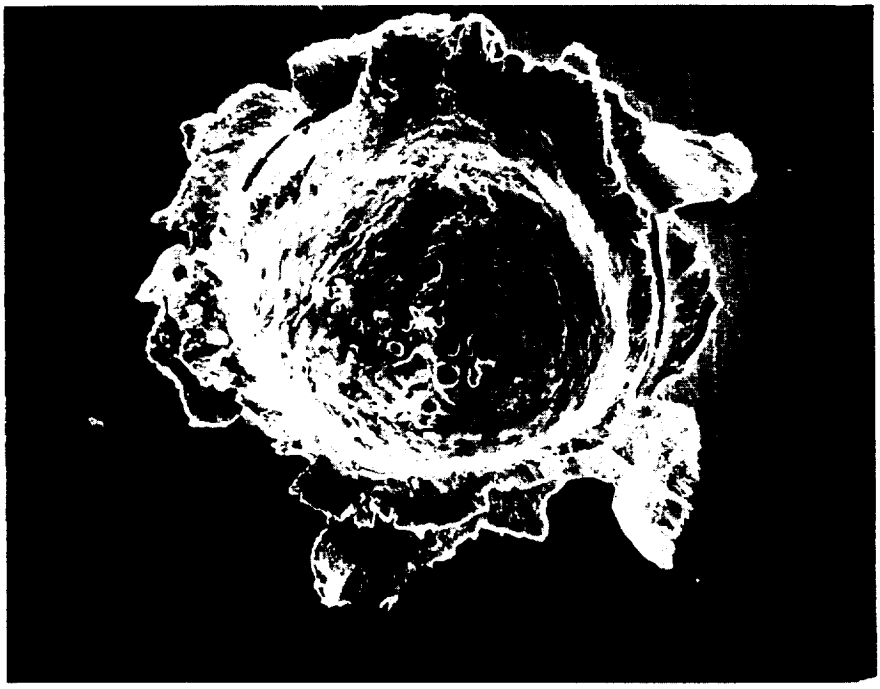
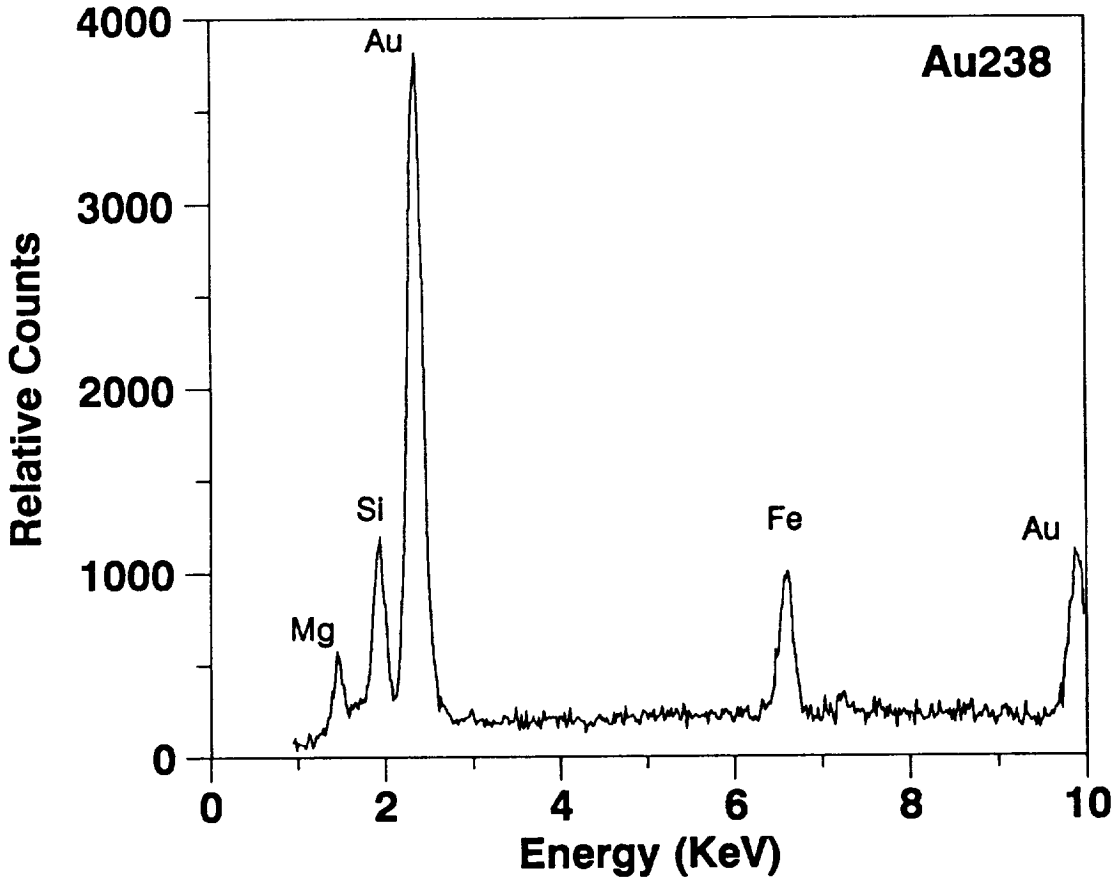


COMPONENT: EOOI
FEATURE: 238
CORE: LD-175

DIAMETER: 100 μm
ORIGIN: Natural



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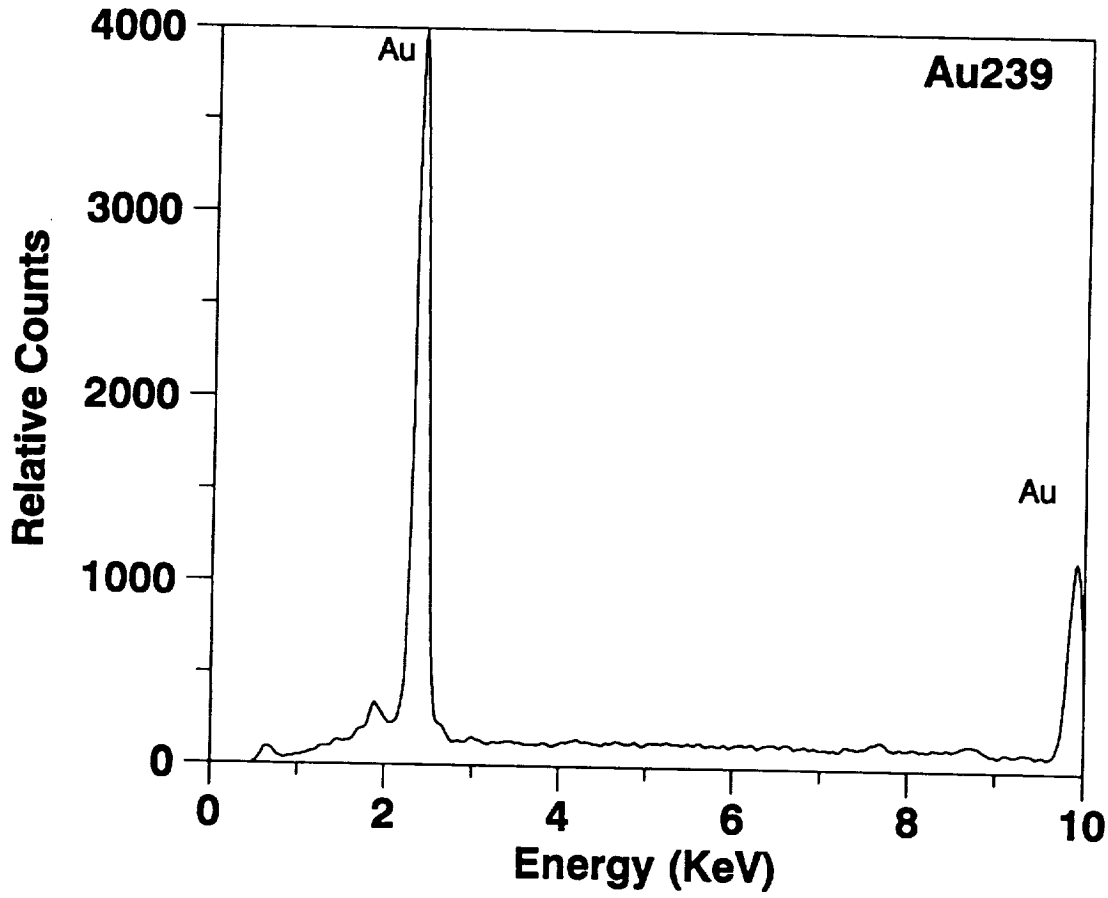
COMPONENT: EOOI
FEATURE: 239
CORE: LD-173

DIAMETER: 160 μm
ORIGIN: Unknown



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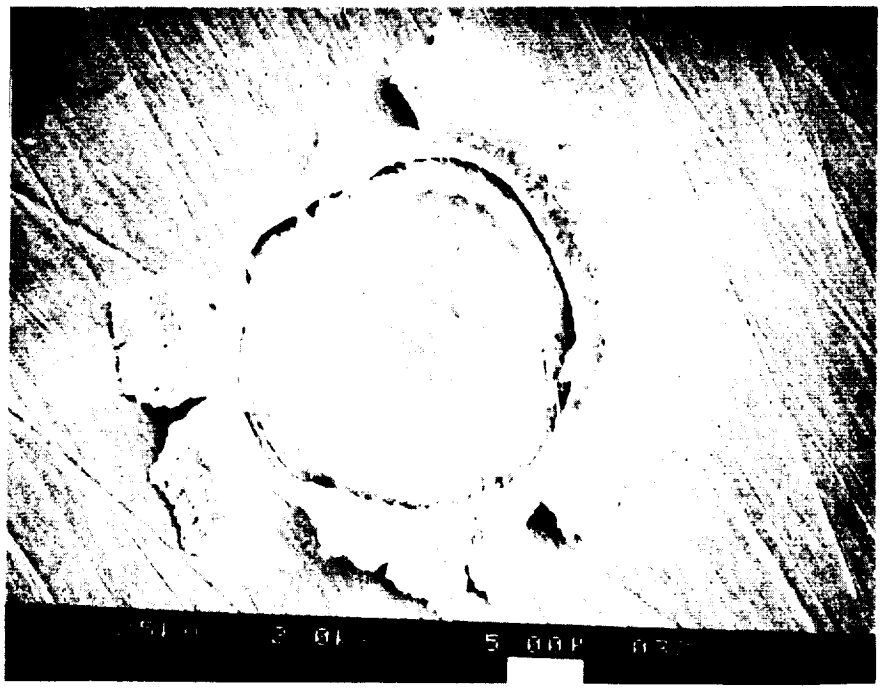
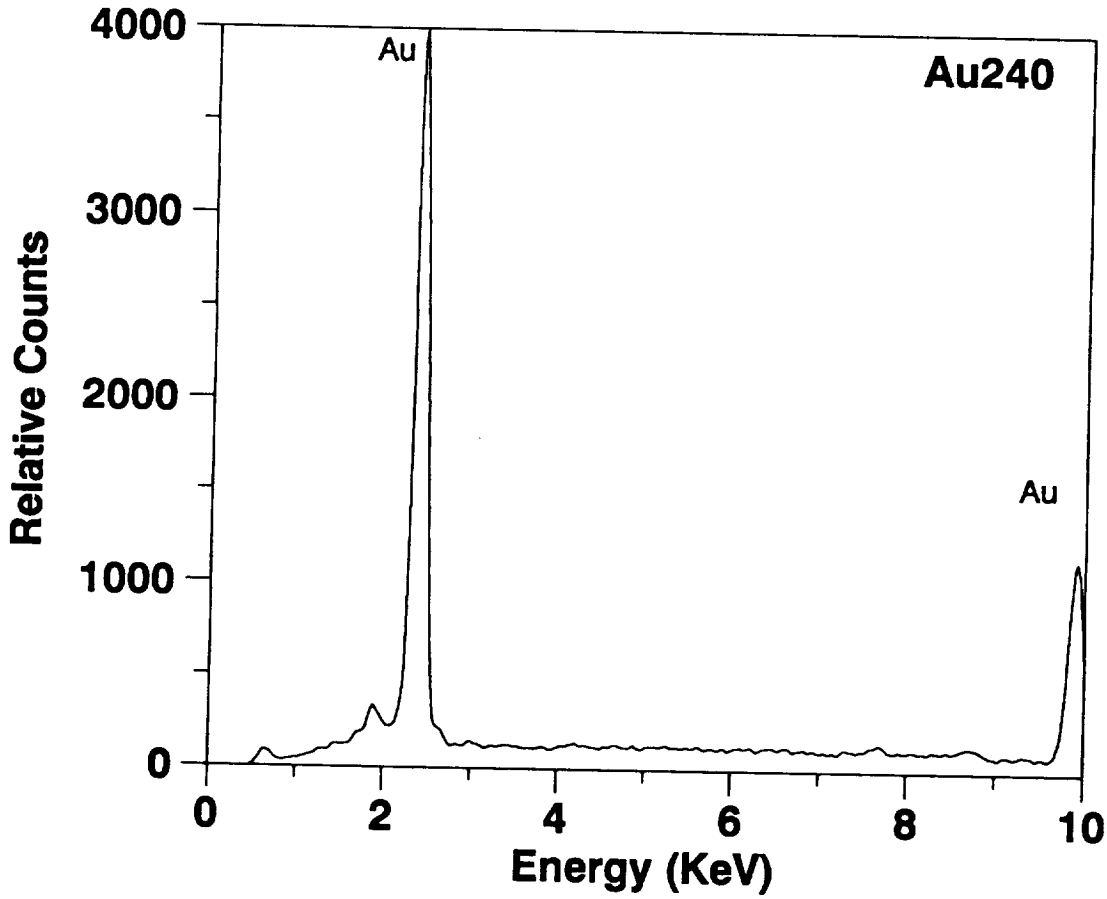


COMPONENT: EOOI
FEATURE: 240
CORE: LD-182

DIAMETER: 15 μm
ORIGIN: Unknown



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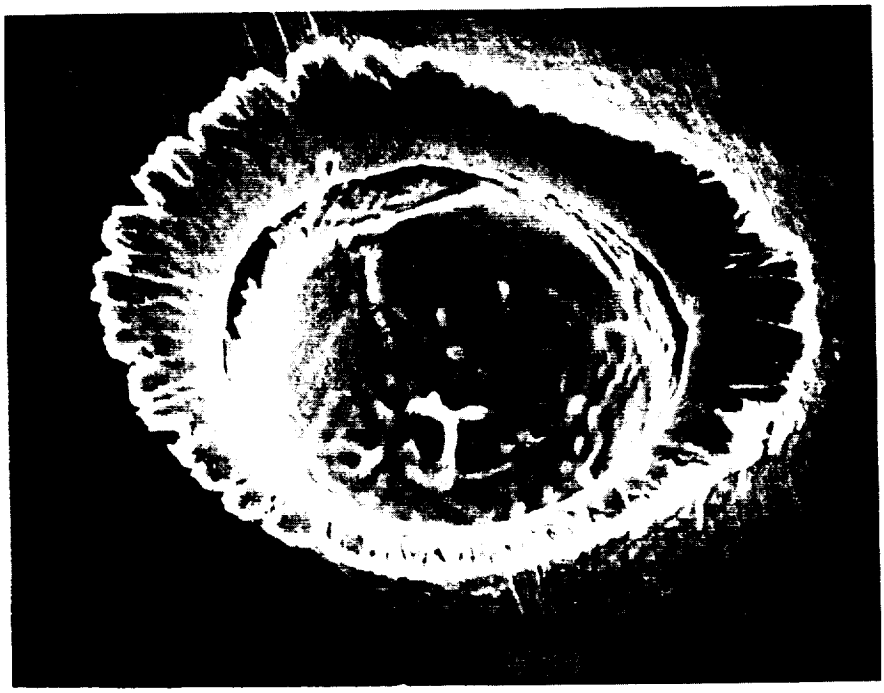
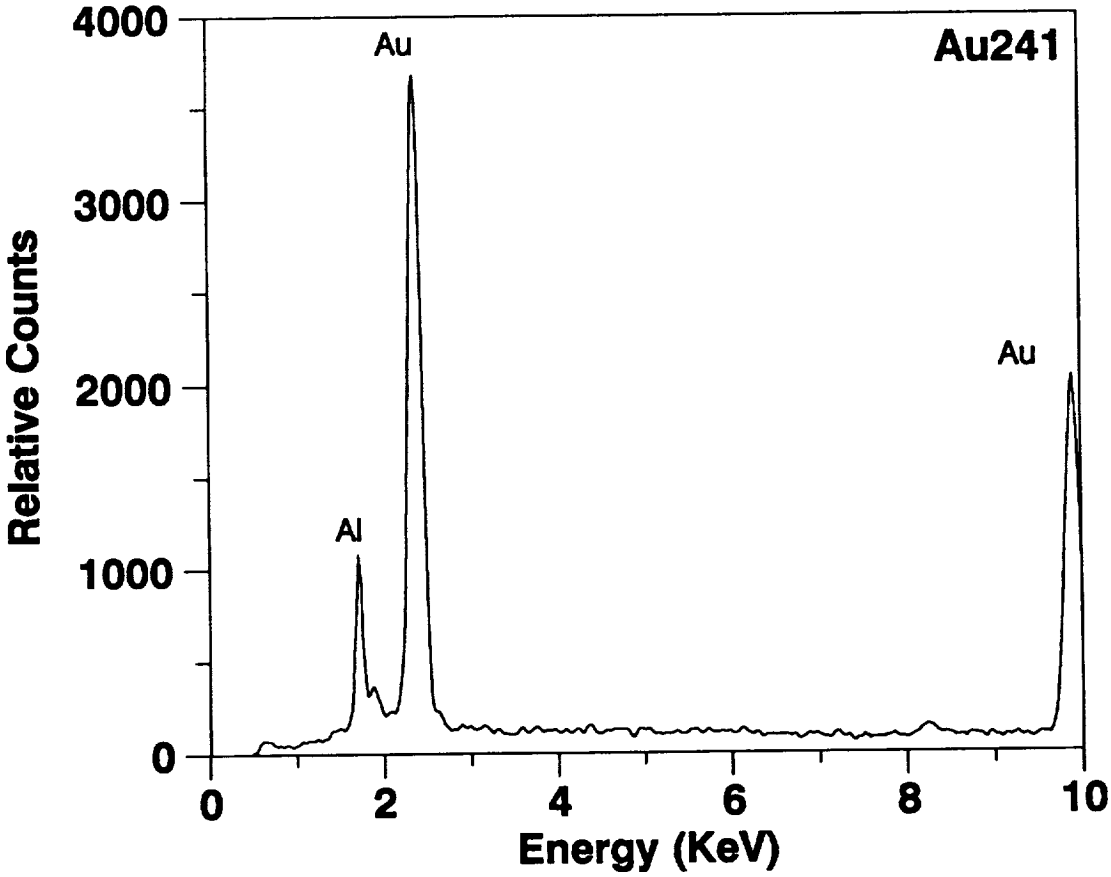


COMPONENT: EOOI
FEATURE: 241
CORE: LD-174

DIAMETER: 20 μm
ORIGIN: Man-made



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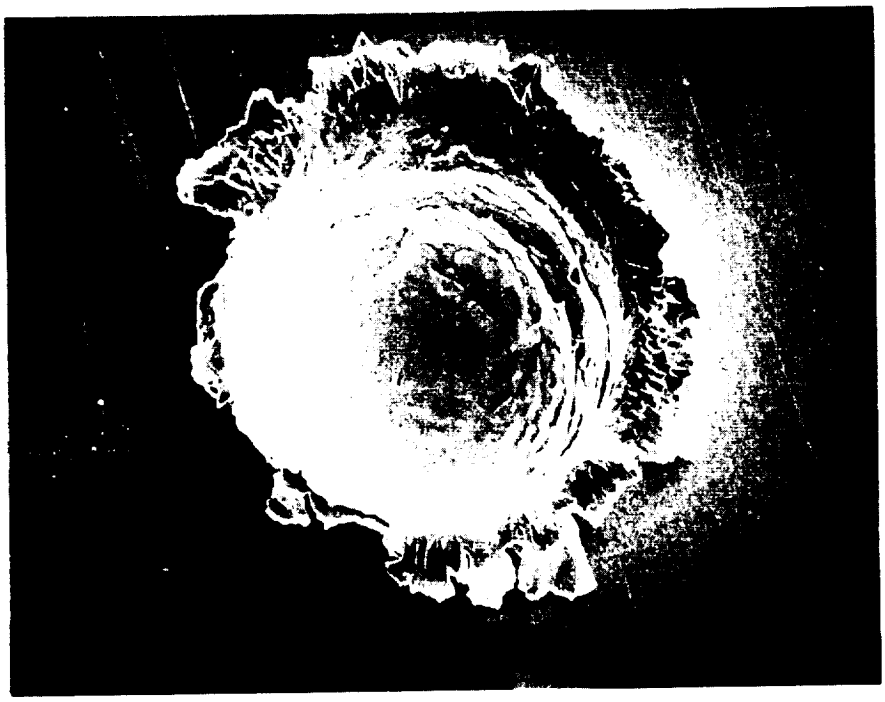
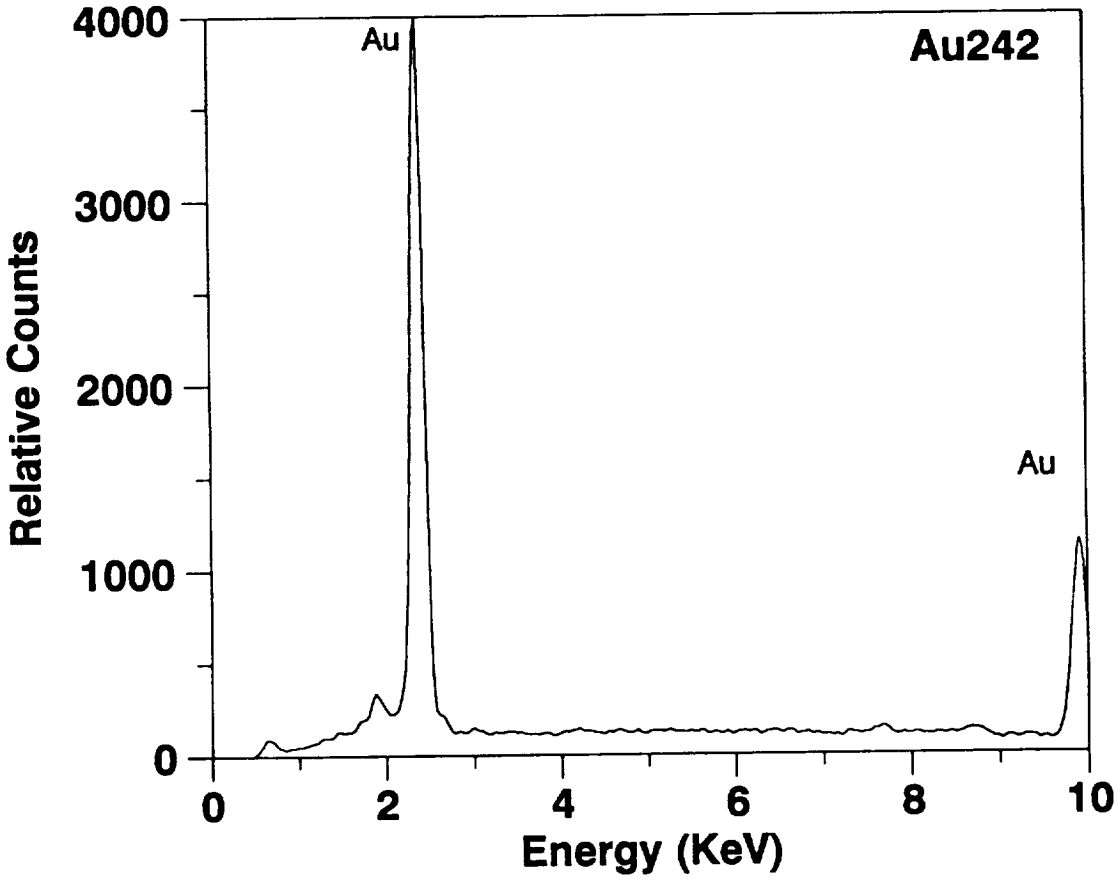


COMPONENT: EOOI
FEATURE: 242
CORE: LD-183

DIAMETER: 95 μm
ORIGIN: Unknown



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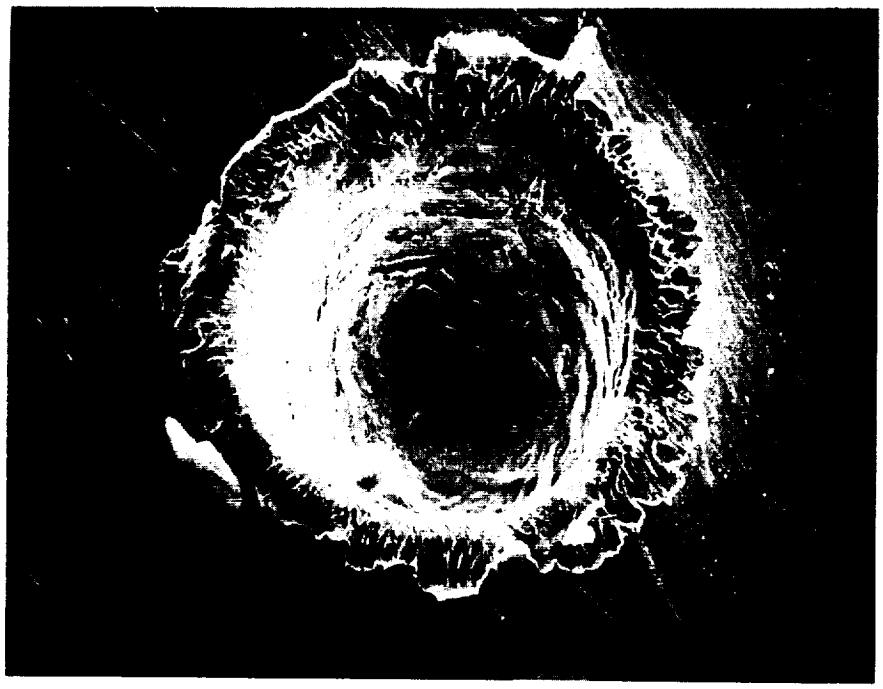
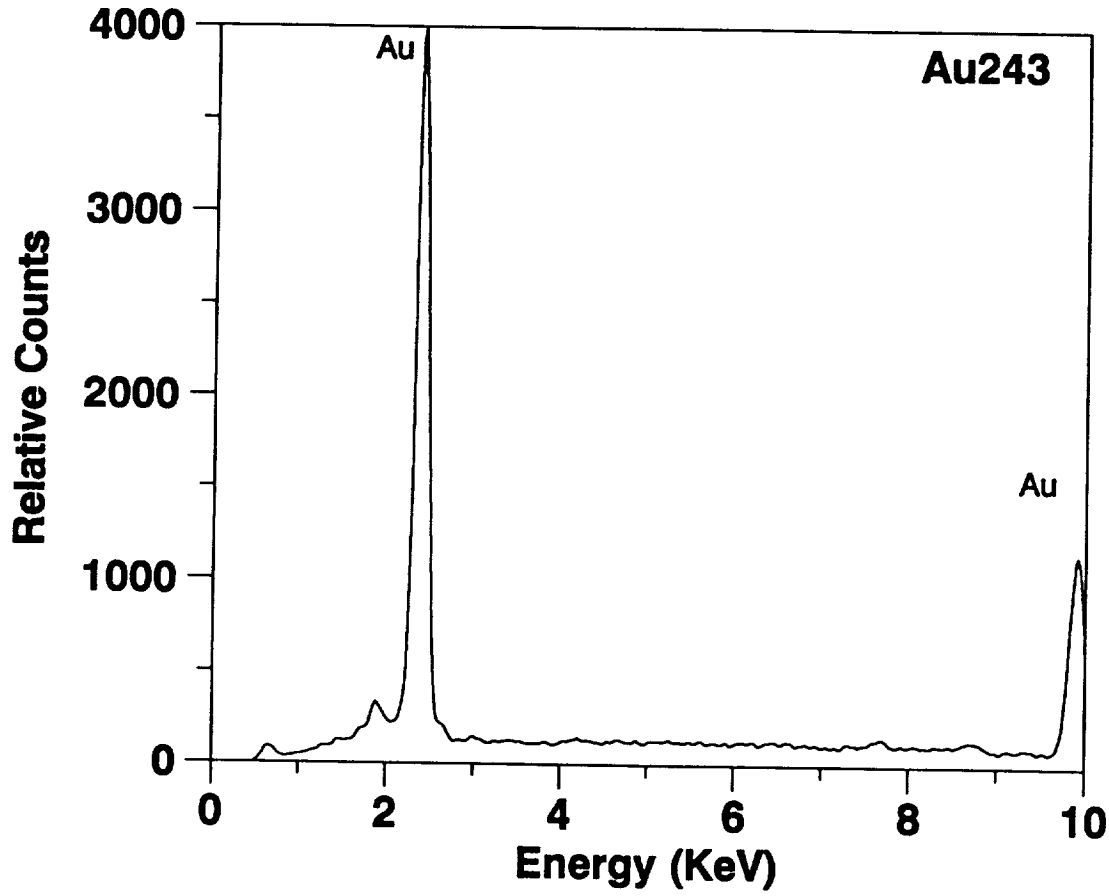


COMPONENT: EOOI
FEATURE: 243
CORE: LD-184

DIAMETER: 125 μm
ORIGIN: Unknown



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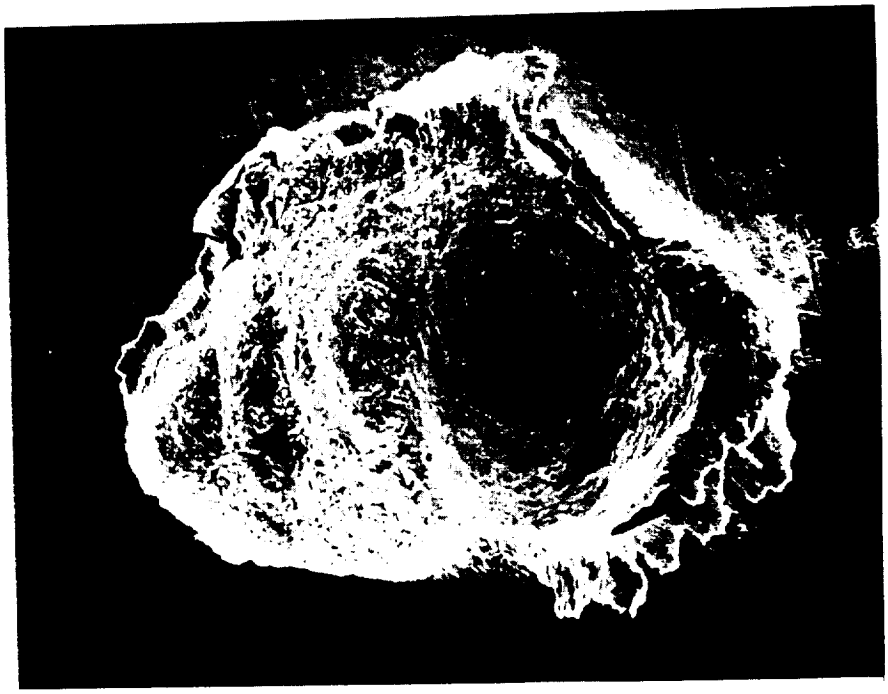
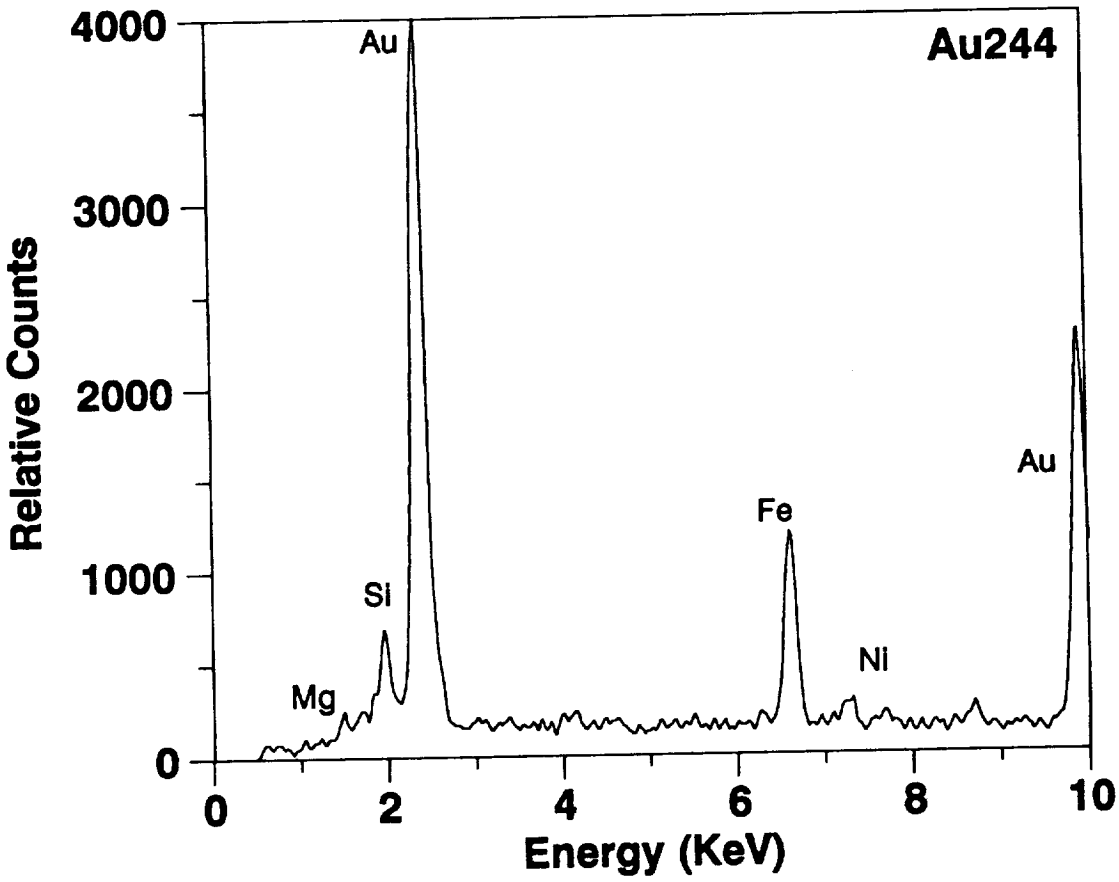


COMPONENT: EOOI
FEATURE: 244
CORE: LD-185

DIAMETER: 80 μm
ORIGIN: Natural



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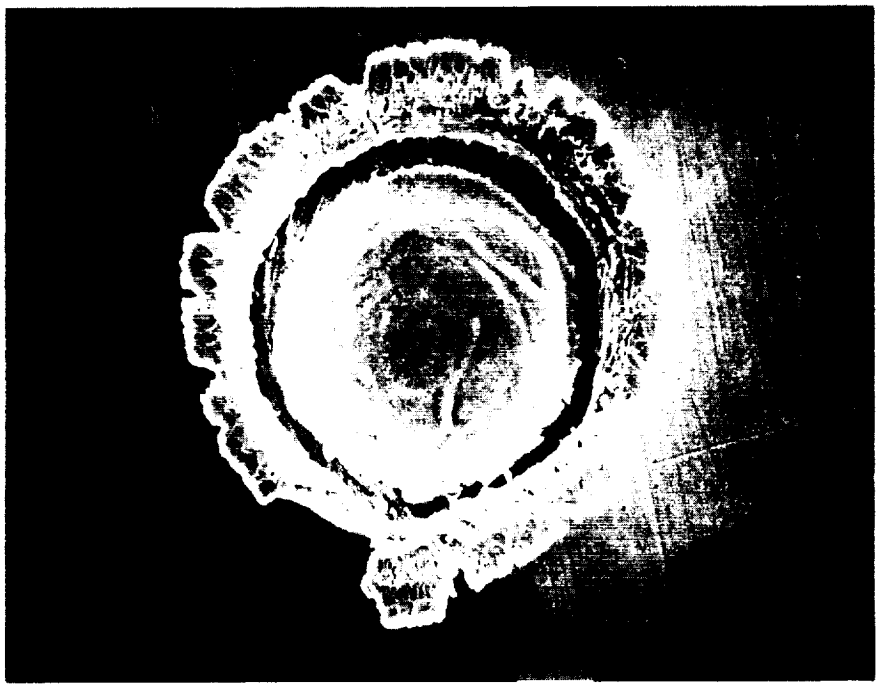
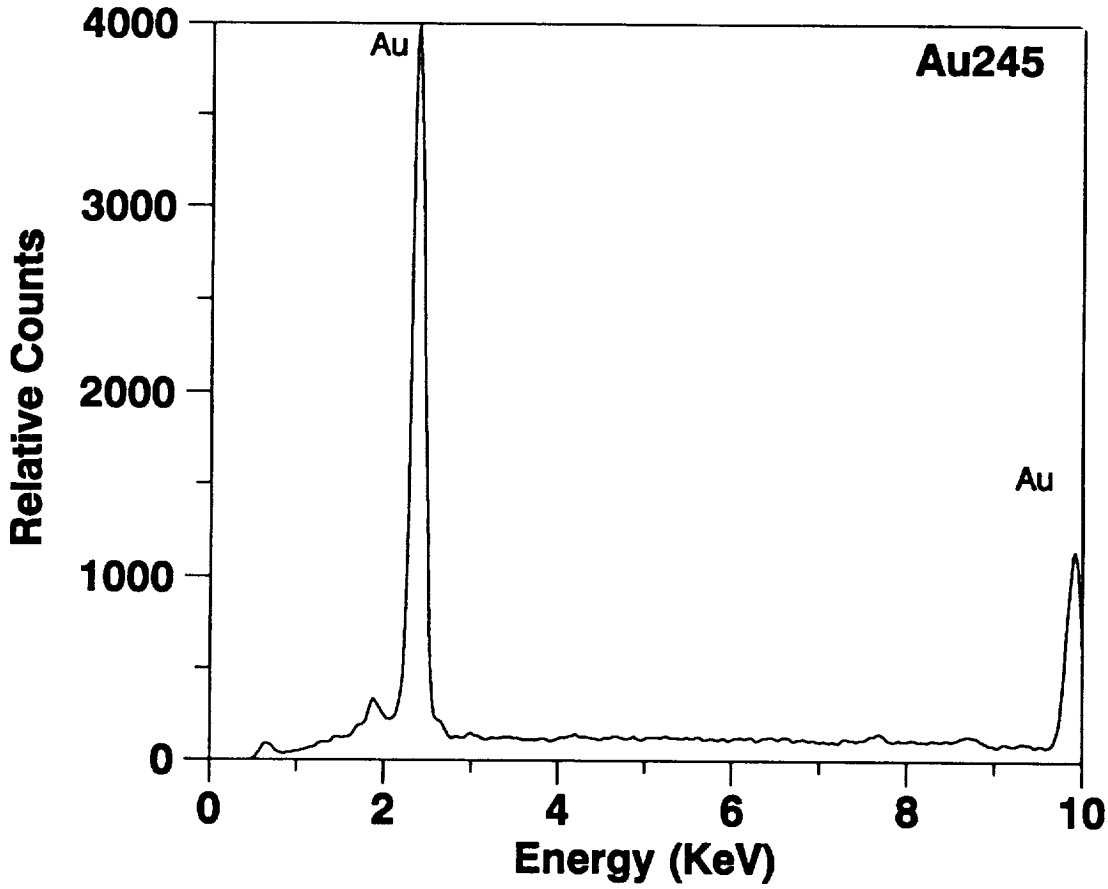


COMPONENT: EOOI
FEATURE: 245
CORE: LD-186

DIAMETER: 30 μm
ORIGIN: Unknown



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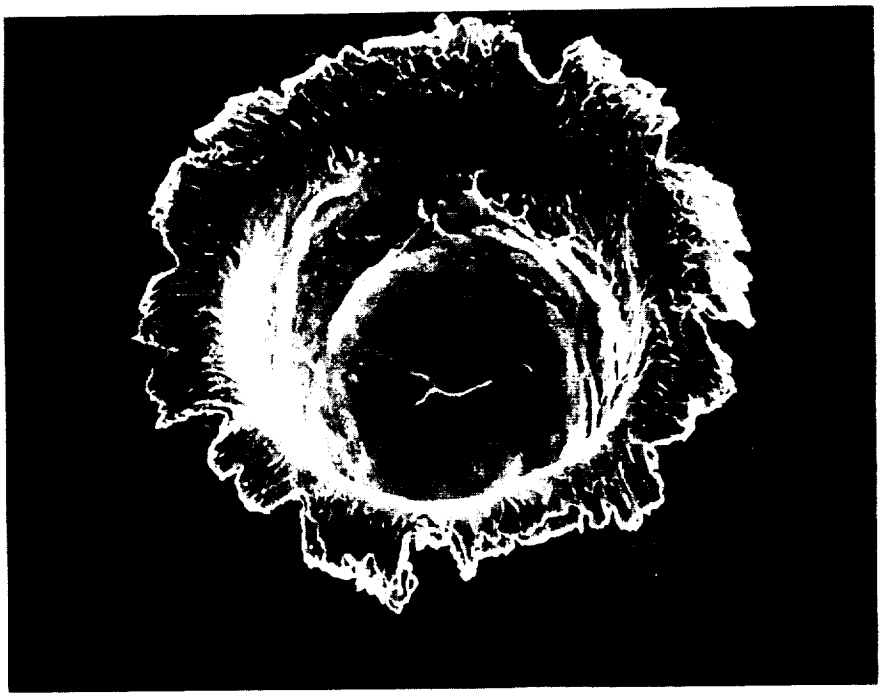
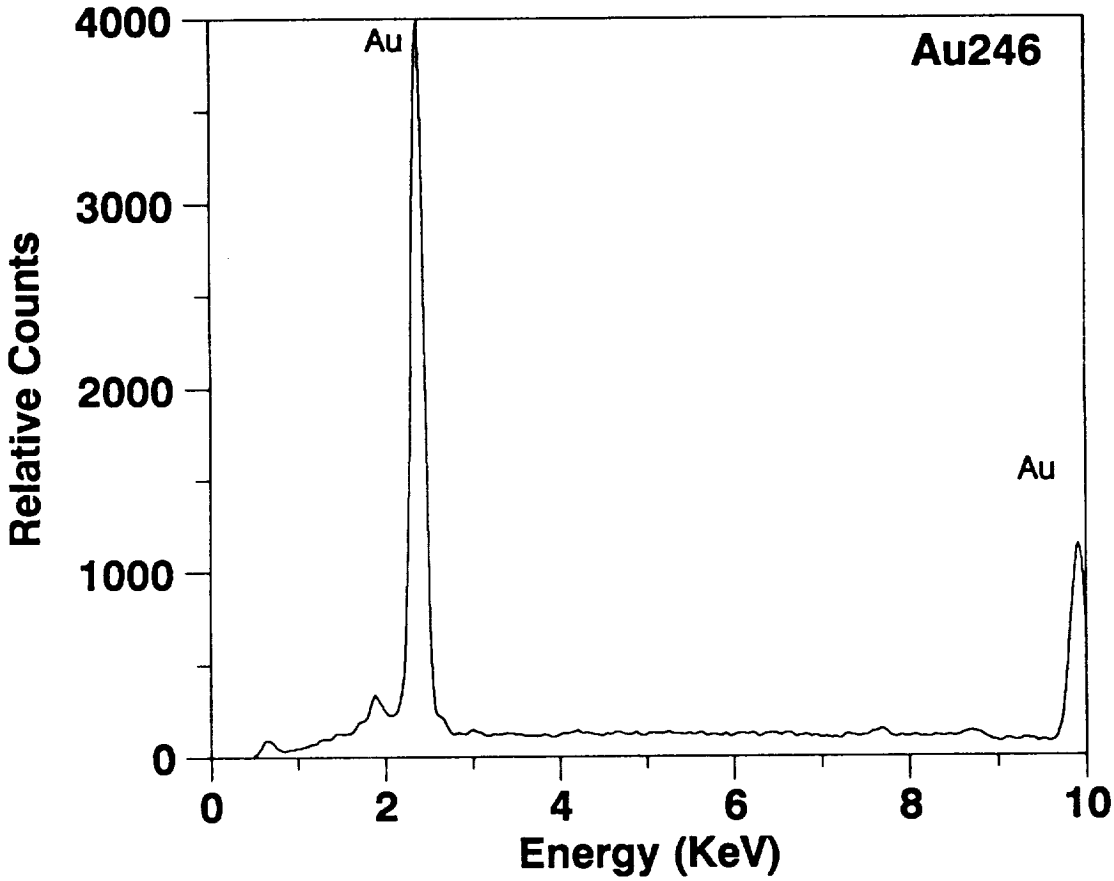


COMPONENT: EOOJ
FEATURE: 246
CORE: LD-227

DIAMETER: 55 μm
ORIGIN: Unknown



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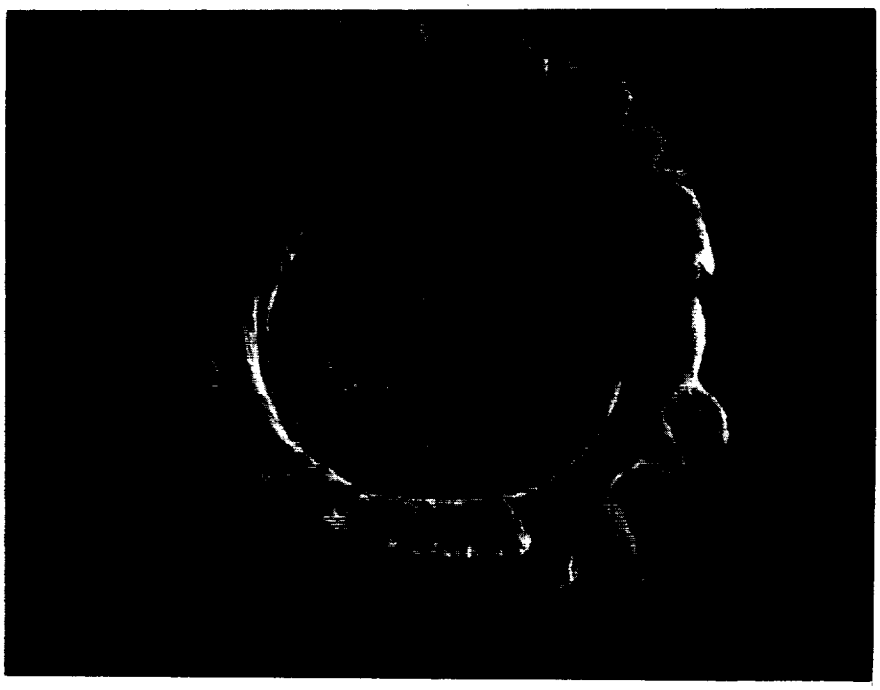
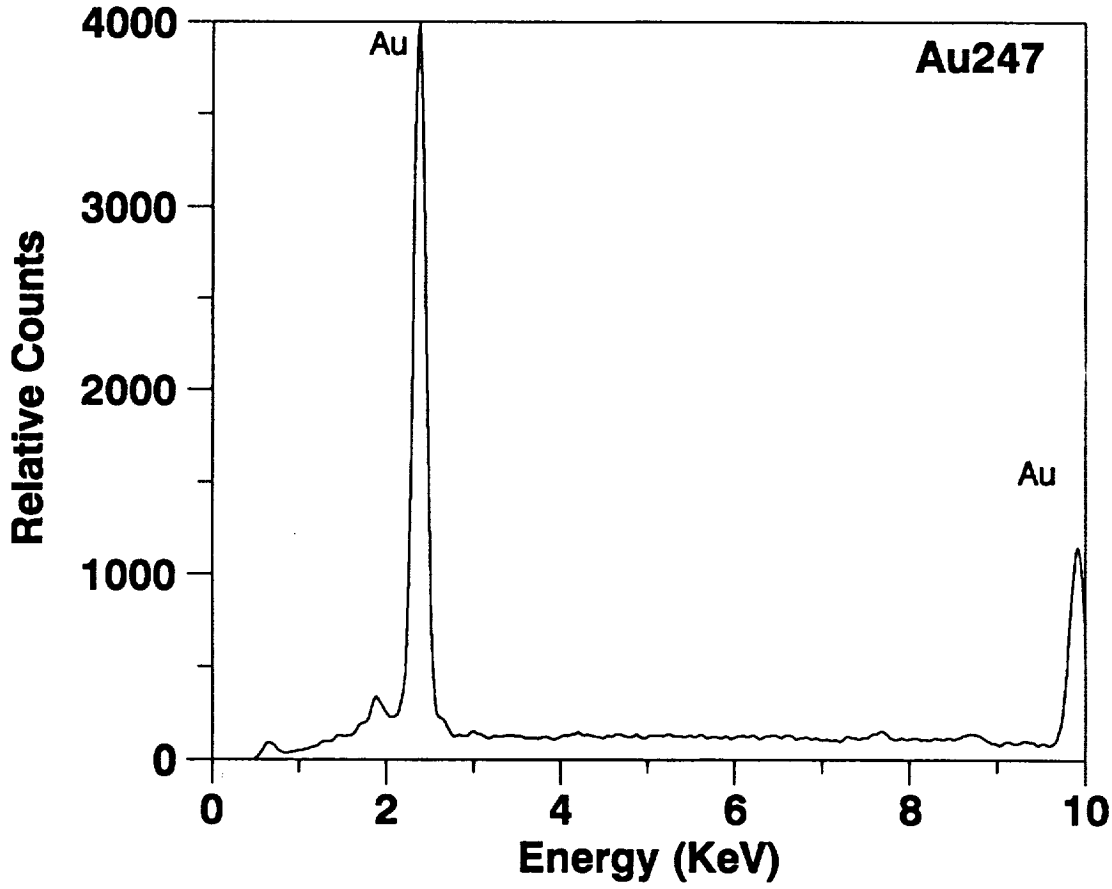


COMPONENT: EOOJ
FEATURE: 247
CORE: LD-201

DIAMETER: 15 μm
ORIGIN: Unknown



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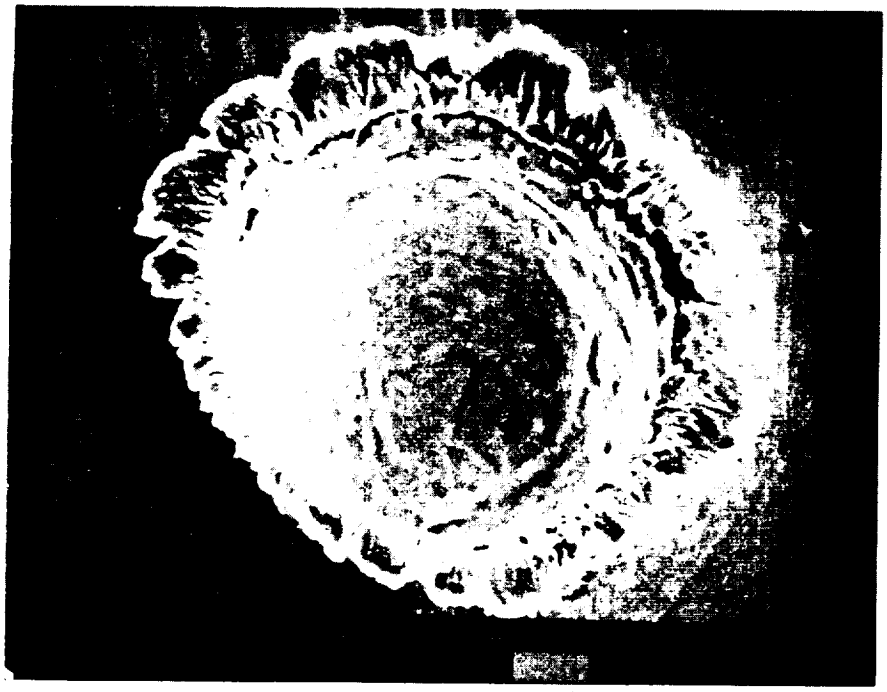
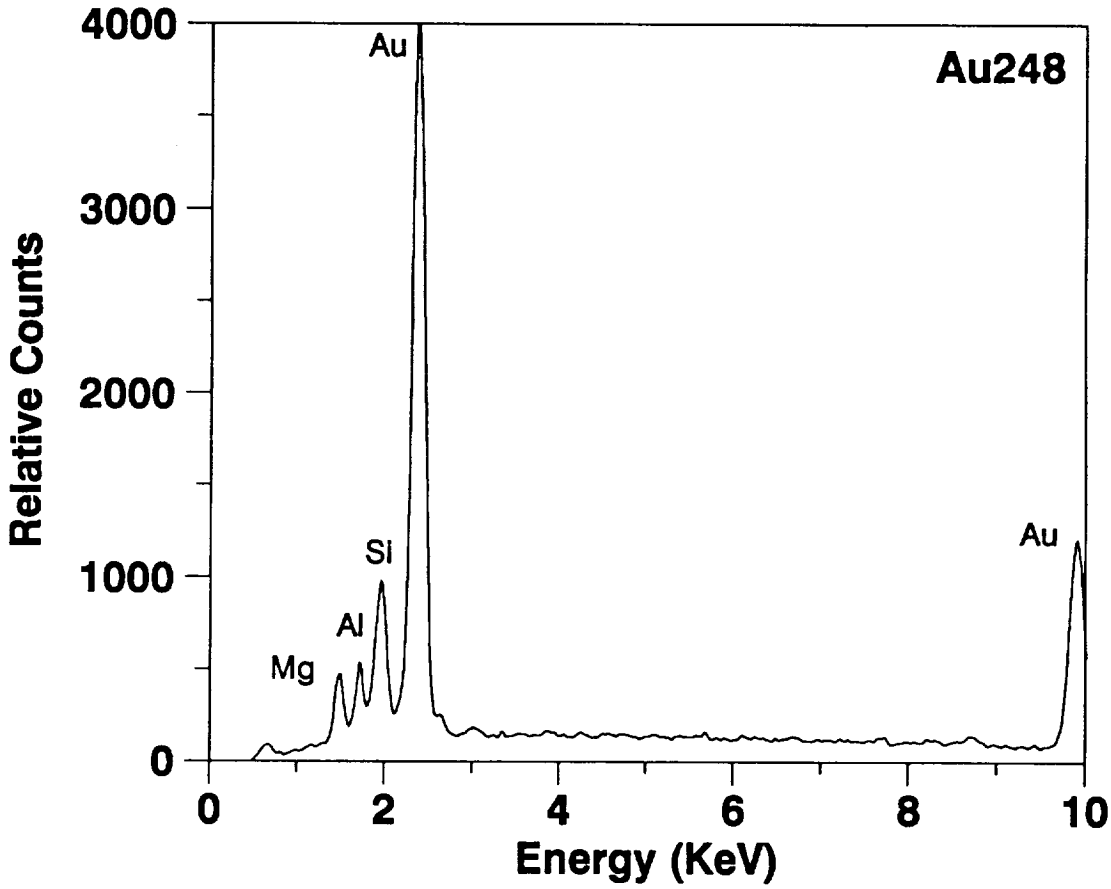


COMPONENT: EOOJ
FEATURE: 248
CORE: LD-202

DIAMETER: 20 μm
ORIGIN: Natural



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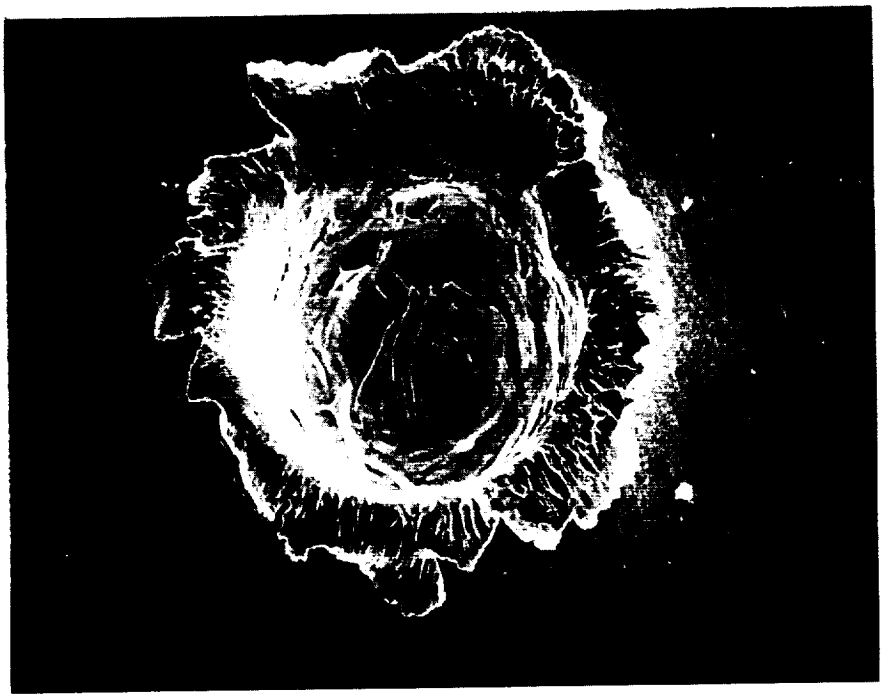
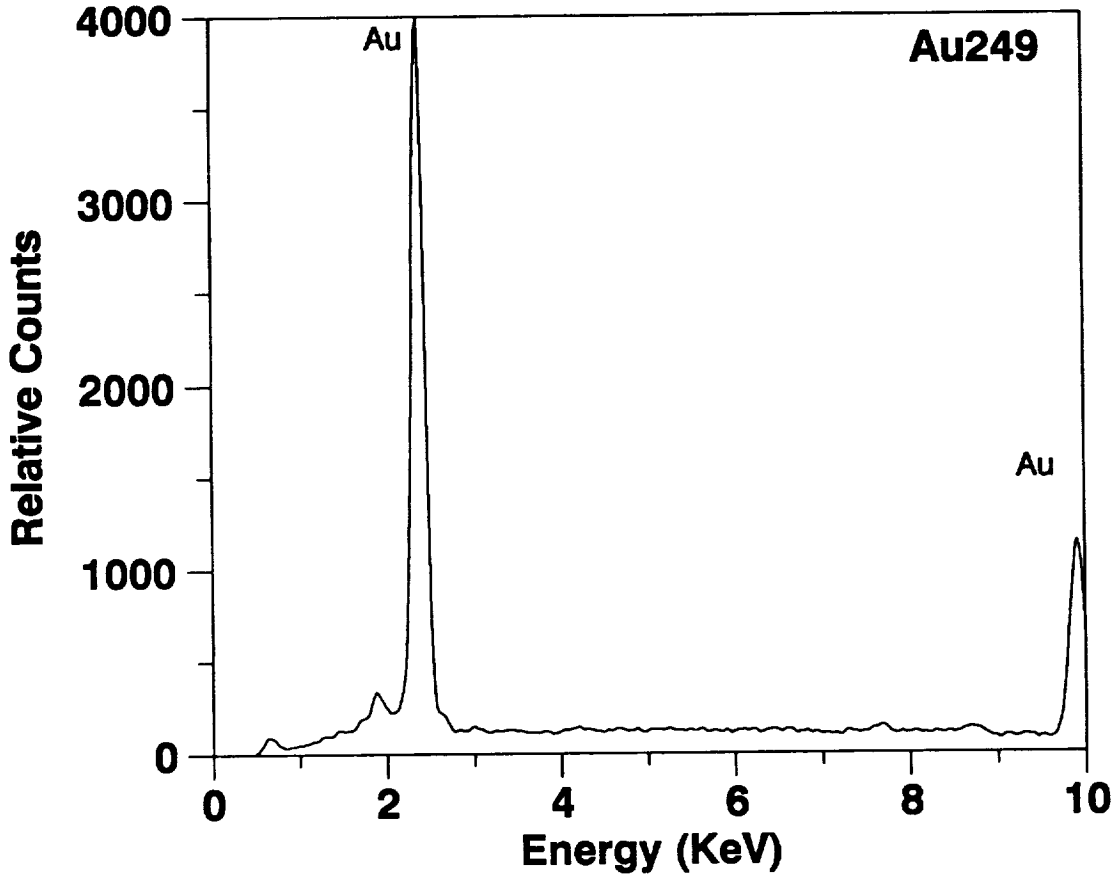


COMPONENT: EOOJ
FEATURE: 249
CORE: LD-203

DIAMETER: 105 μm
ORIGIN: Unknown



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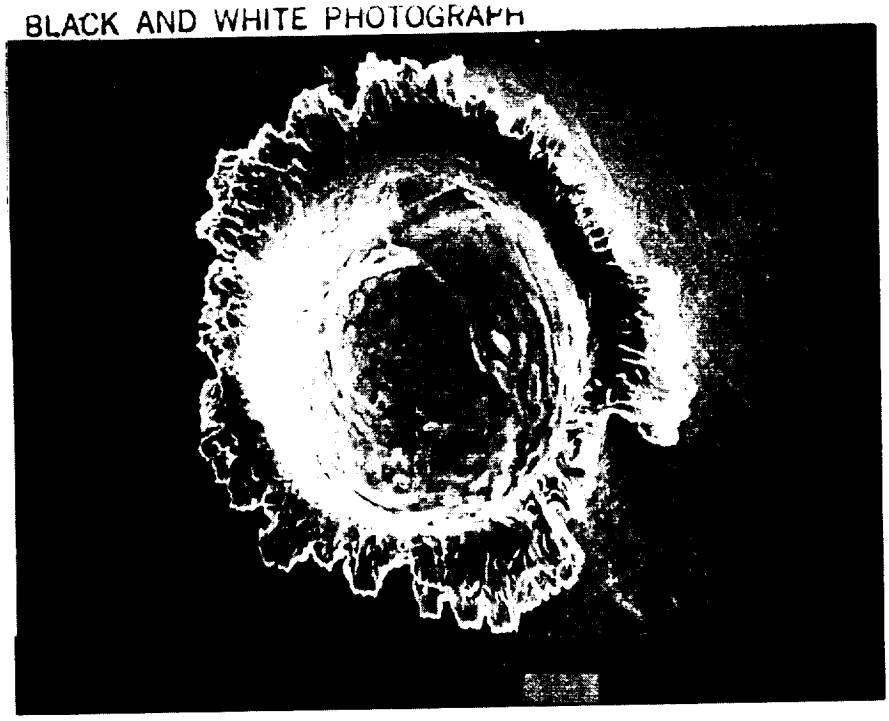
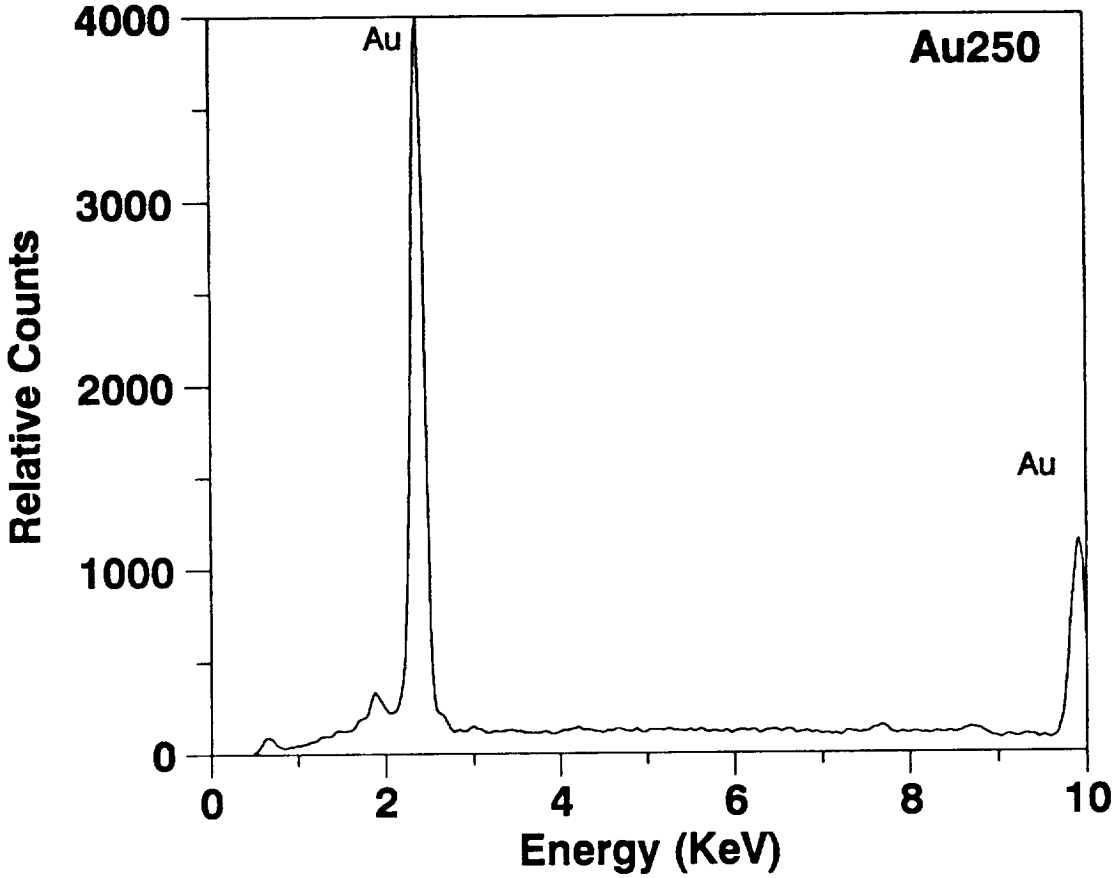


COMPONENT: EOOJ
FEATURE: 250
CORE: LD-204

DIAMETER: 55 μm
ORIGIN: Unknown



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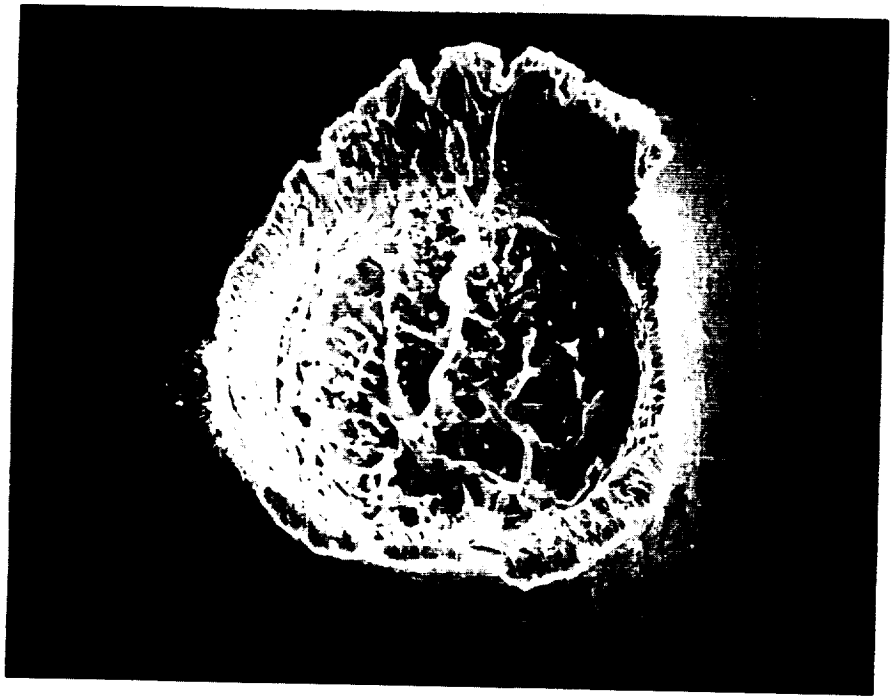
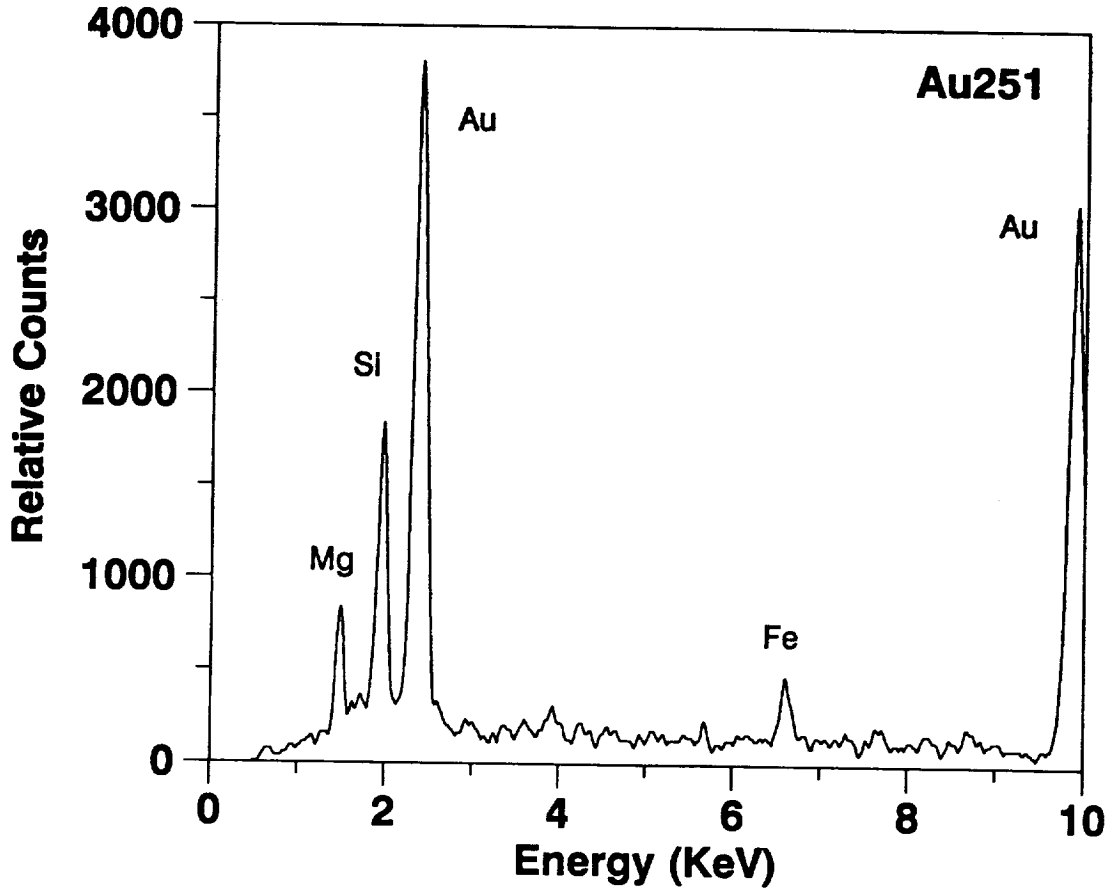


COMPONENT: EOOJ
FEATURE: 251
CORE: LD-205

DIAMETER: 45 μm
ORIGIN: Natural



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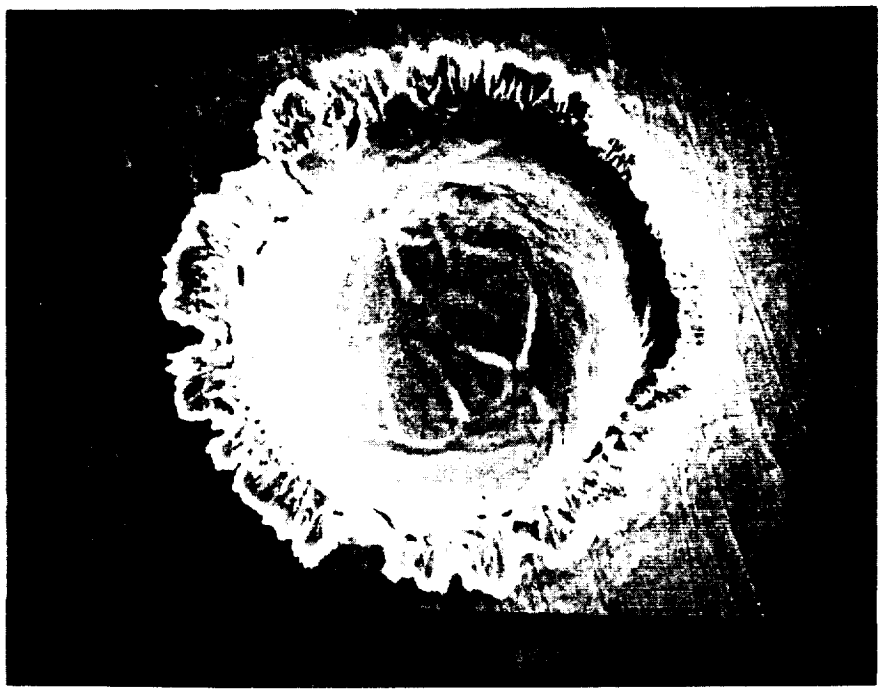
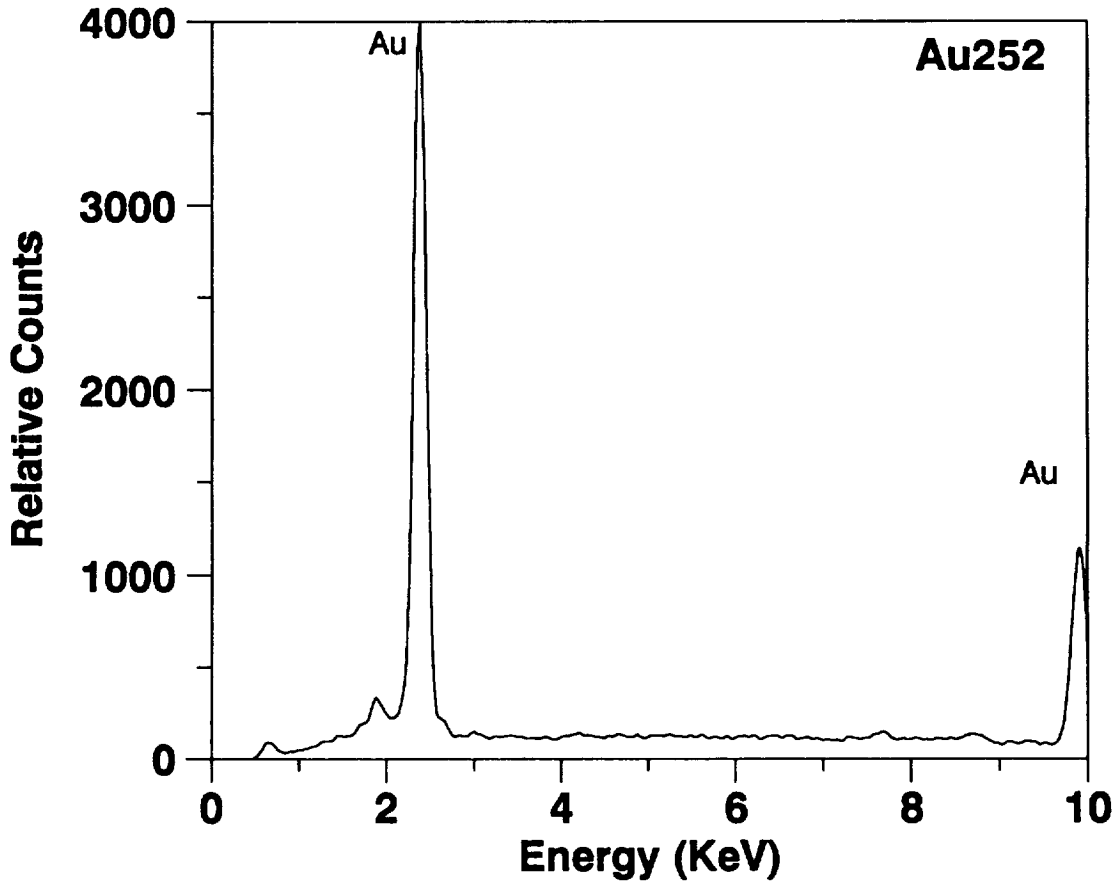


COMPONENT: EOOJ
FEATURE: 252
CORE: LD-206

DIAMETER: 25 μm
ORIGIN: Unknown



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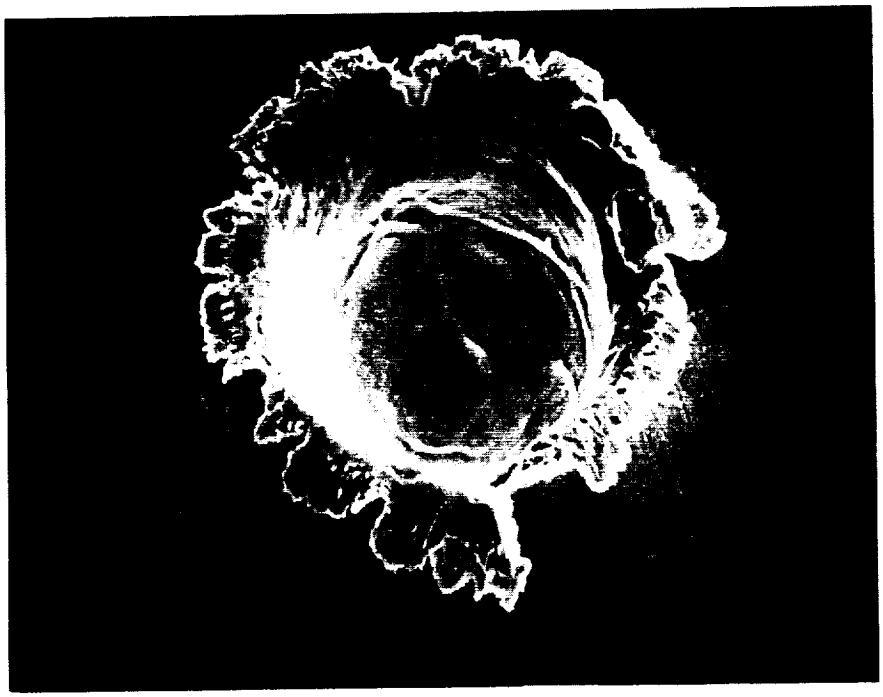
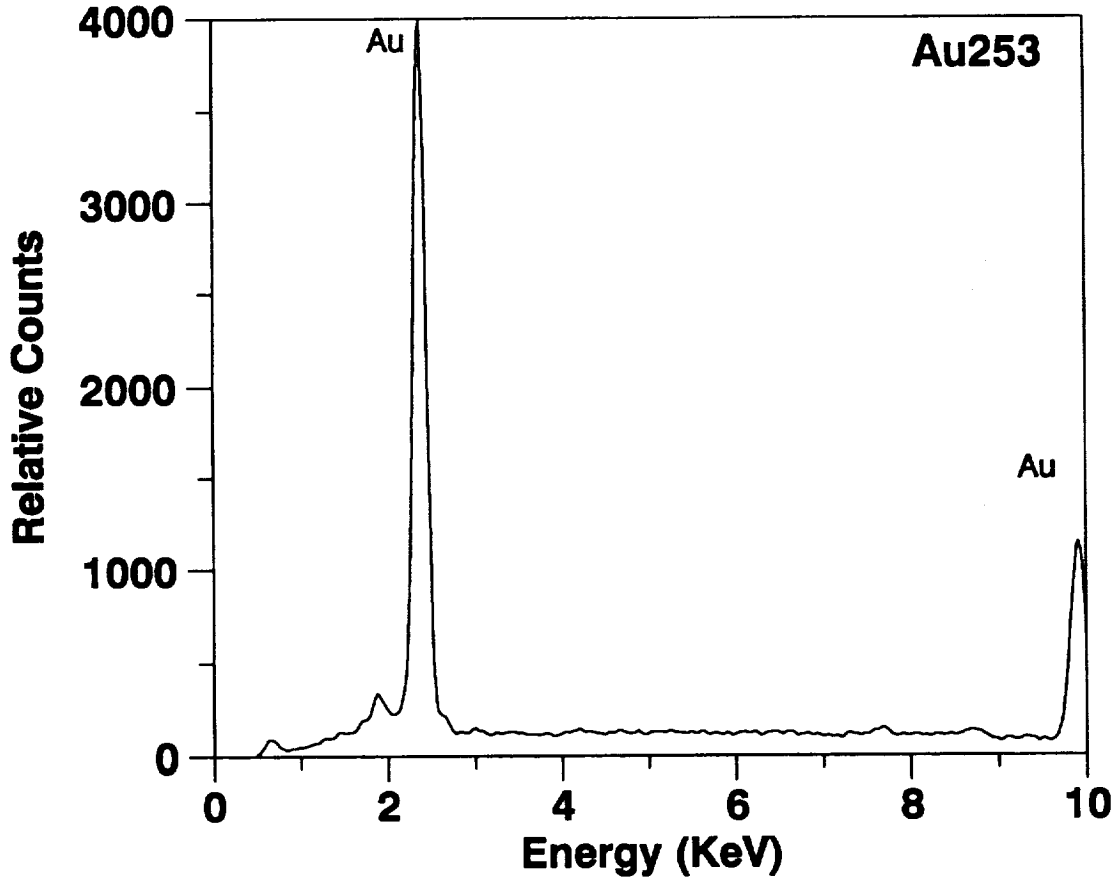


COMPONENT: EOOJ
FEATURE: 253
CORE: LD-207

DIAMETER: 30 μm
ORIGIN: Unknown



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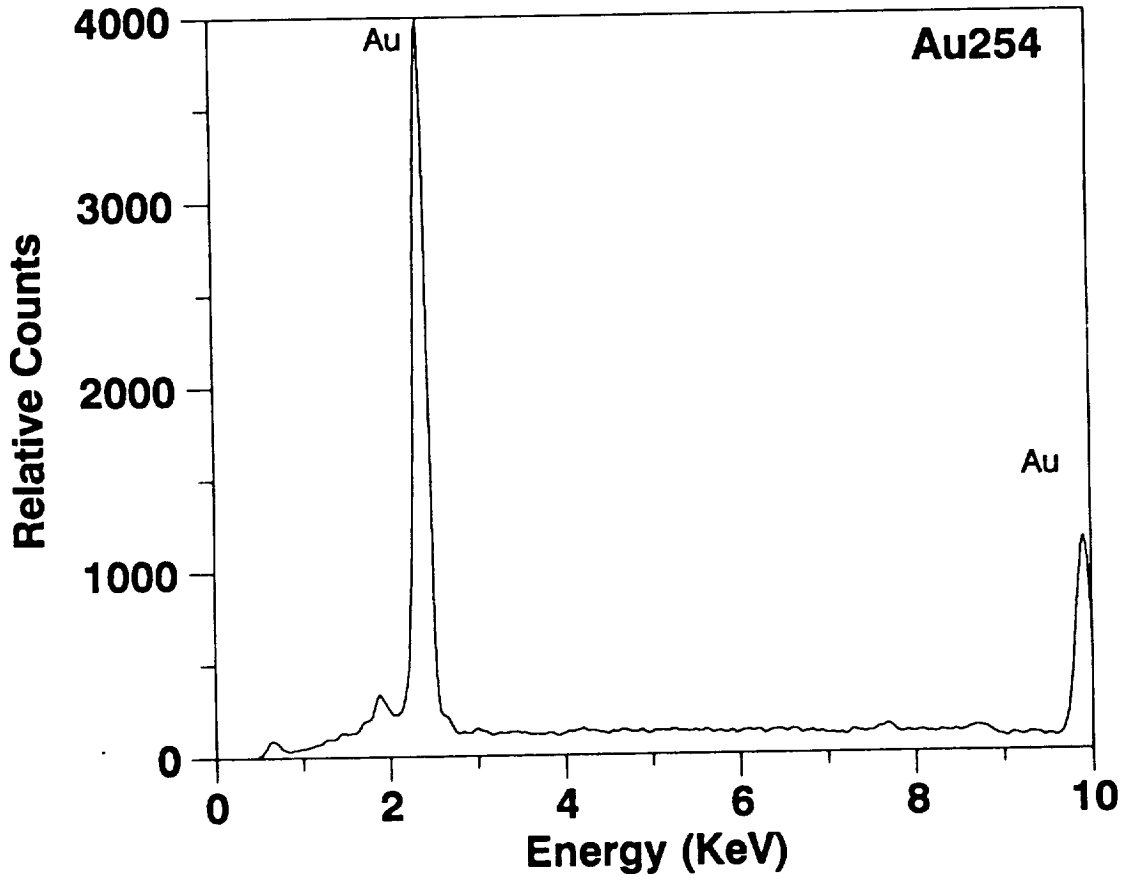
COMPONENT: EOOJ
FEATURE: 254
CORE: LD-208

DIAMETER: 45 μm
ORIGIN: Unknown



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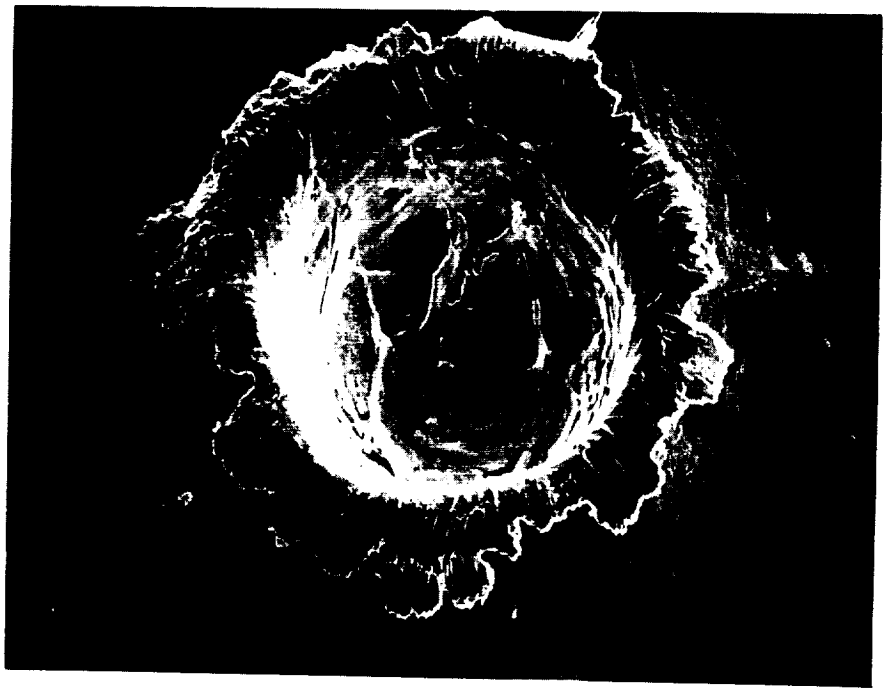
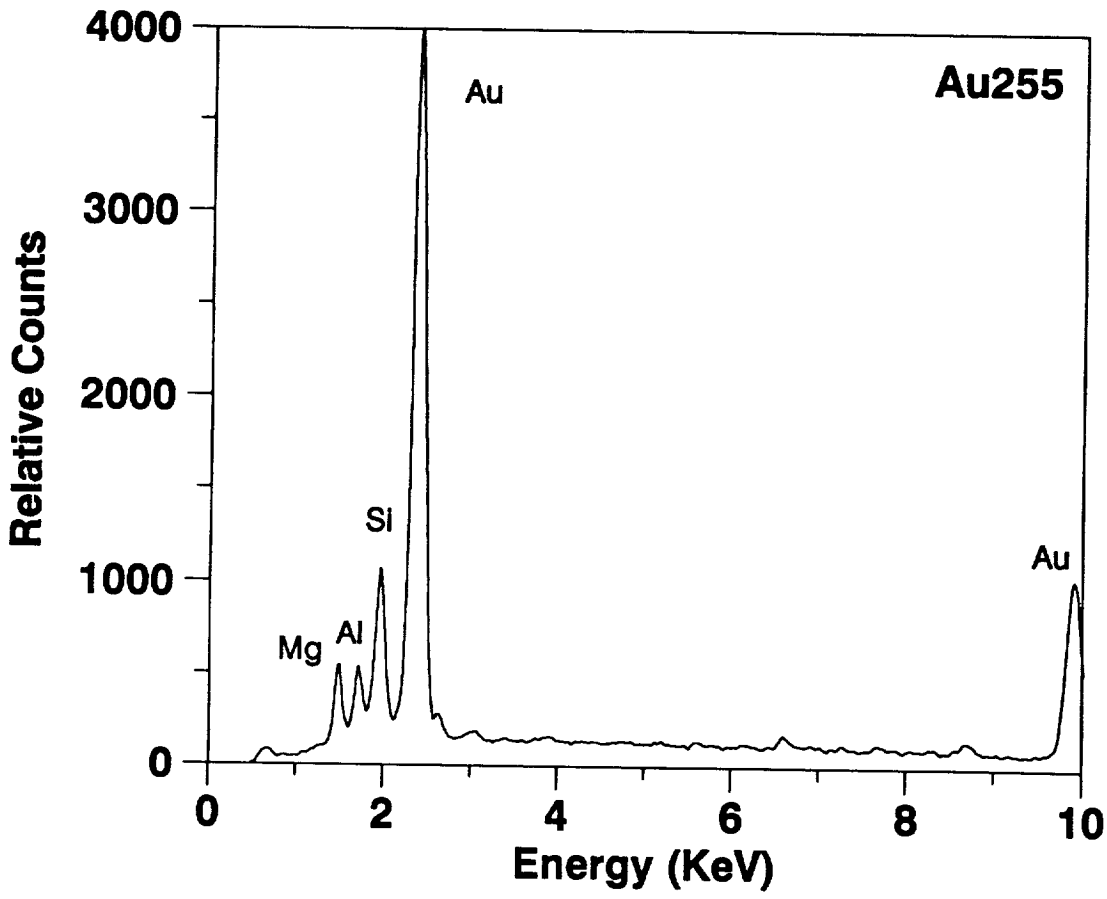


COMPONENT: EOOJ
FEATURE: 255
CORE: LD-209

DIAMETER: 100 μm
ORIGIN: Natural



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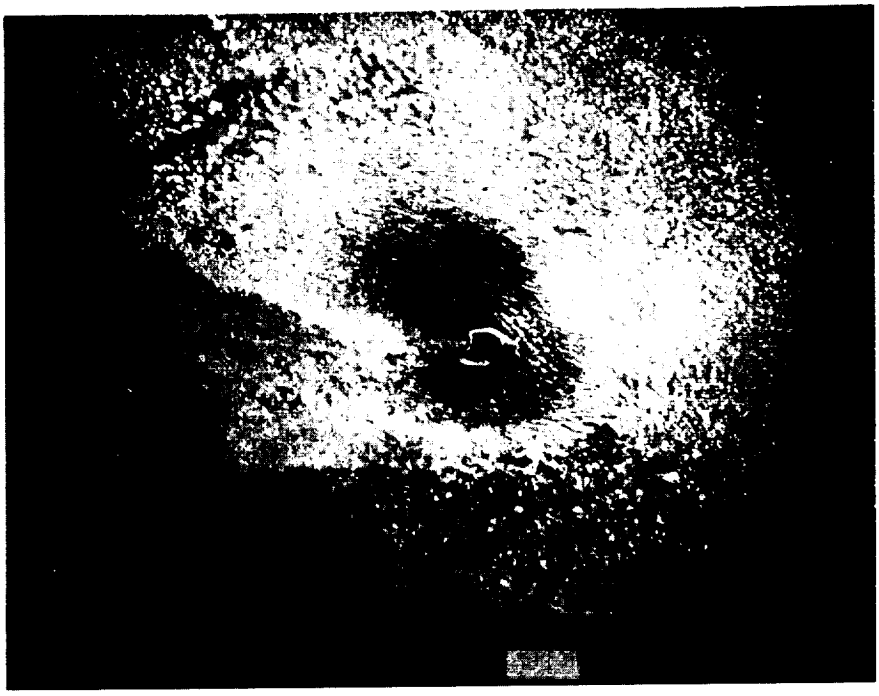
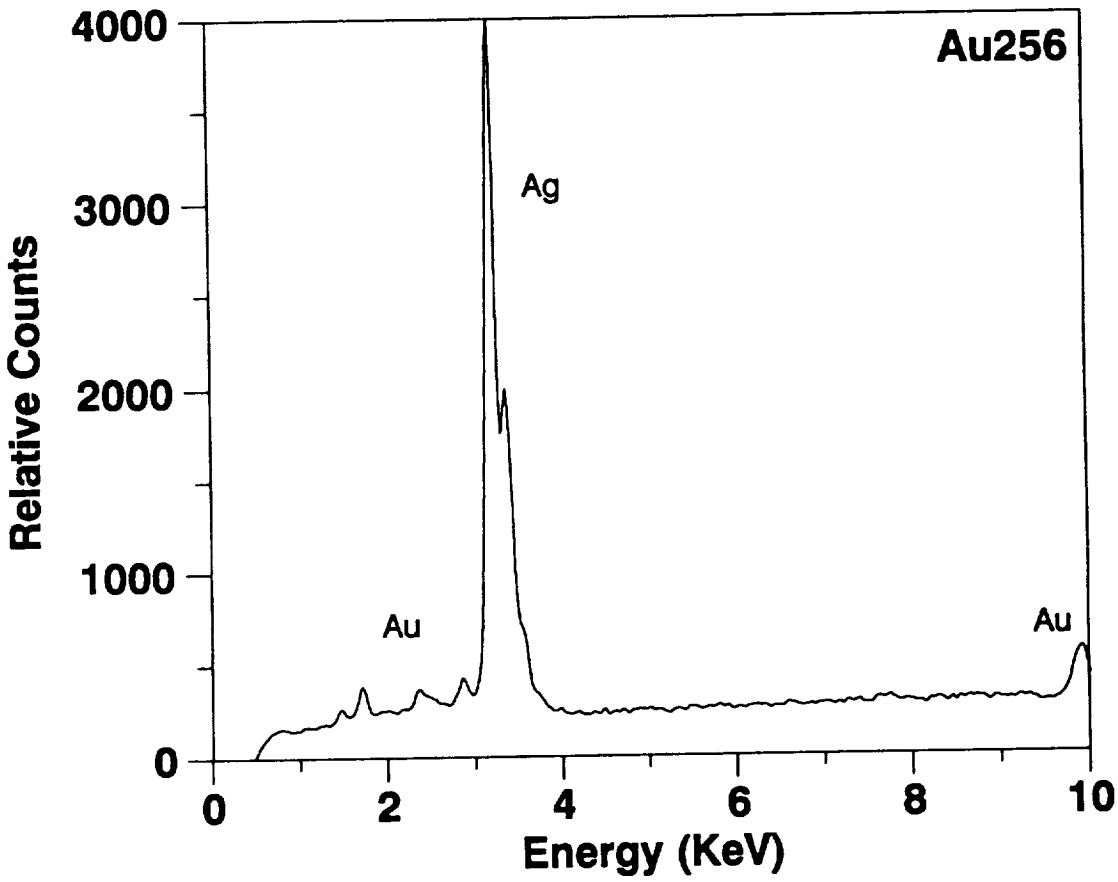


COMPONENT: EOOJ
FEATURE: 256
CORE: LD-210

DIAMETER: 60 μm
ORIGIN: Man-made



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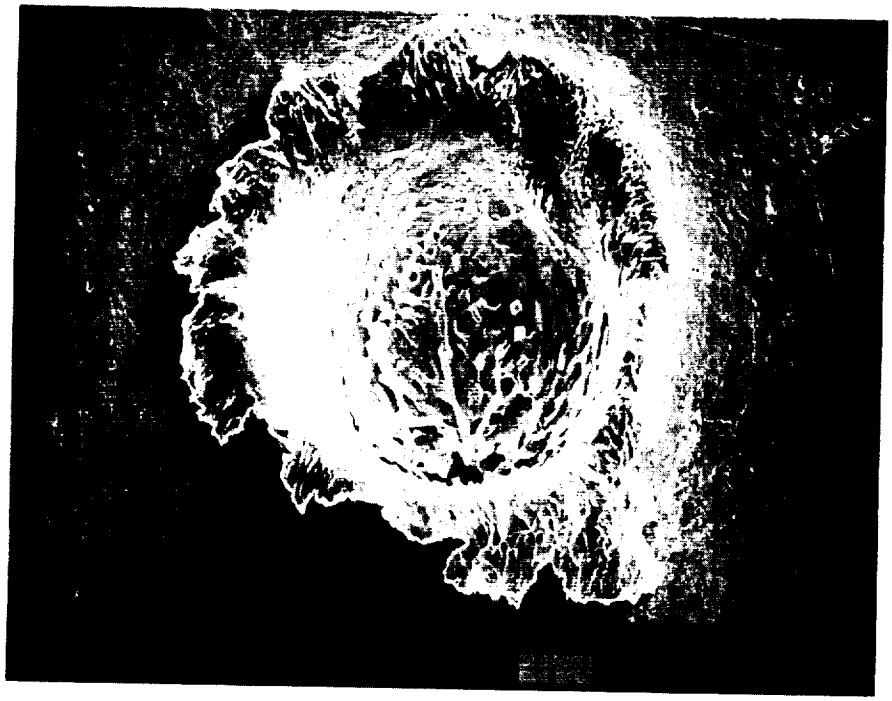
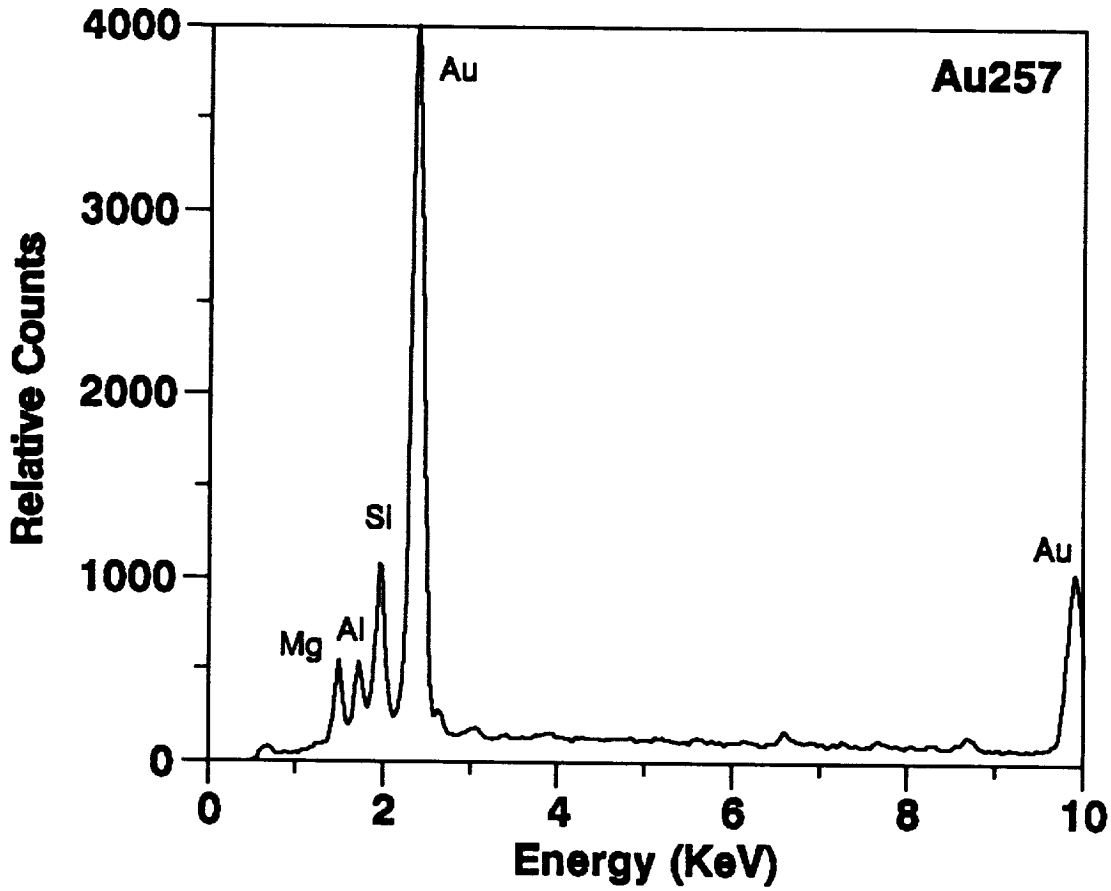


COMPONENT: EOOJ
FEATURE: 257
CORE: LD-211

DIAMETER: 95 μm
ORIGIN: Natural



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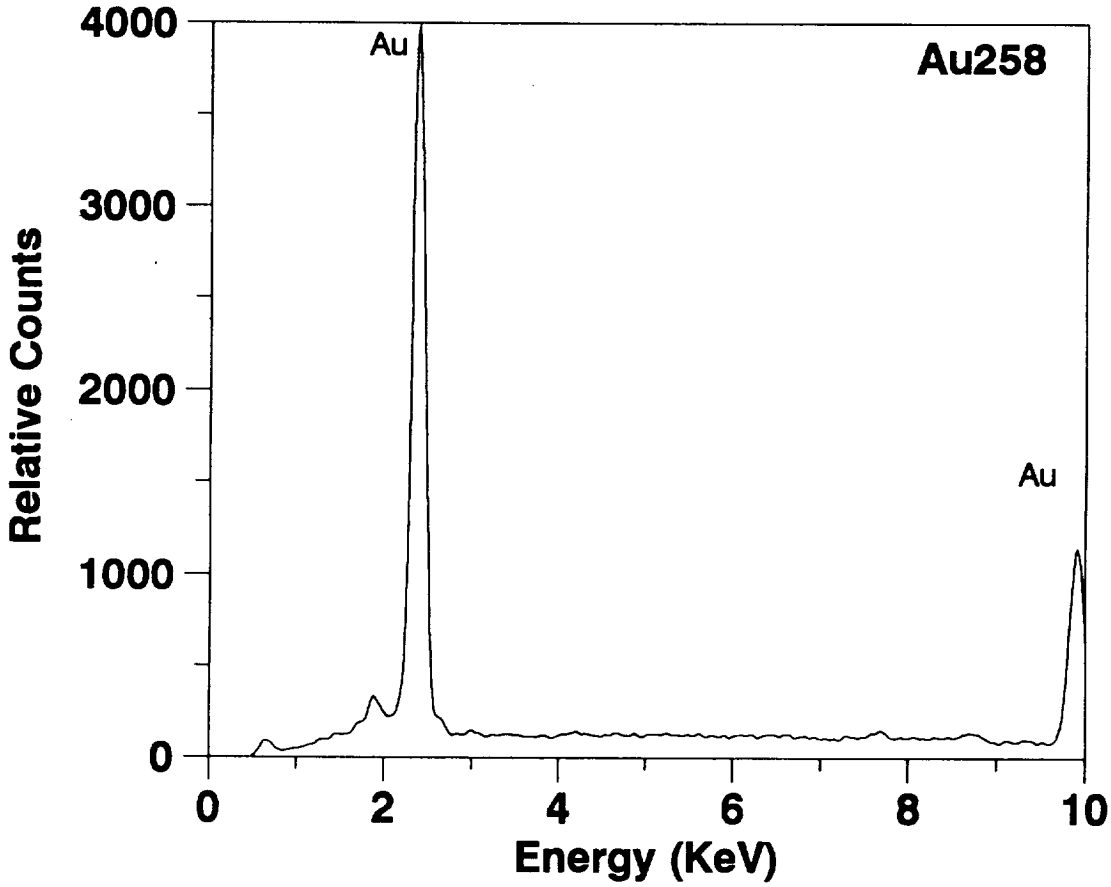
COMPONENT: EOOJ
FEATURE: 258
CORE: LD-226

DIAMETER: 45 μm
ORIGIN: Unknown



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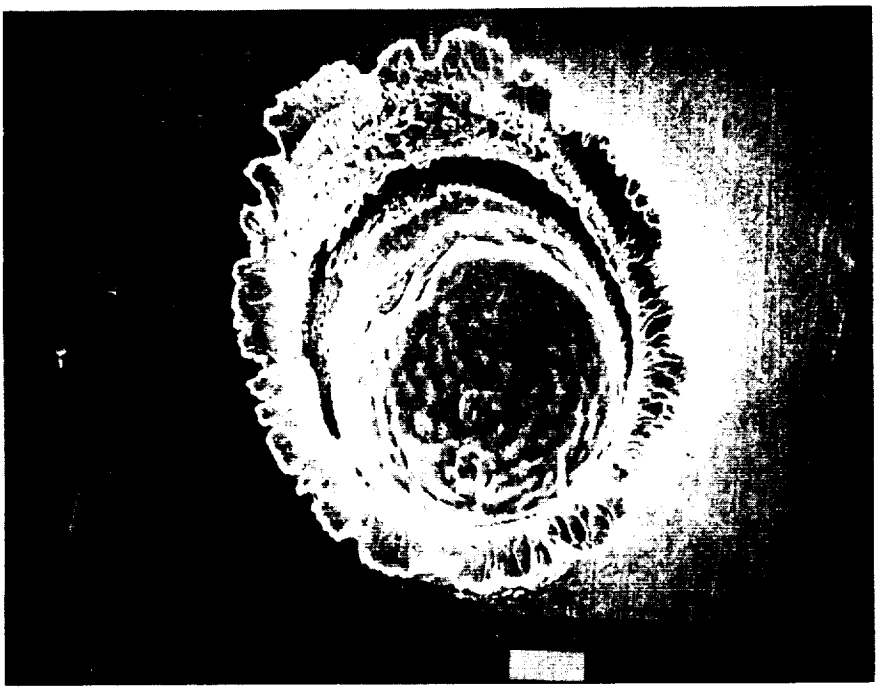
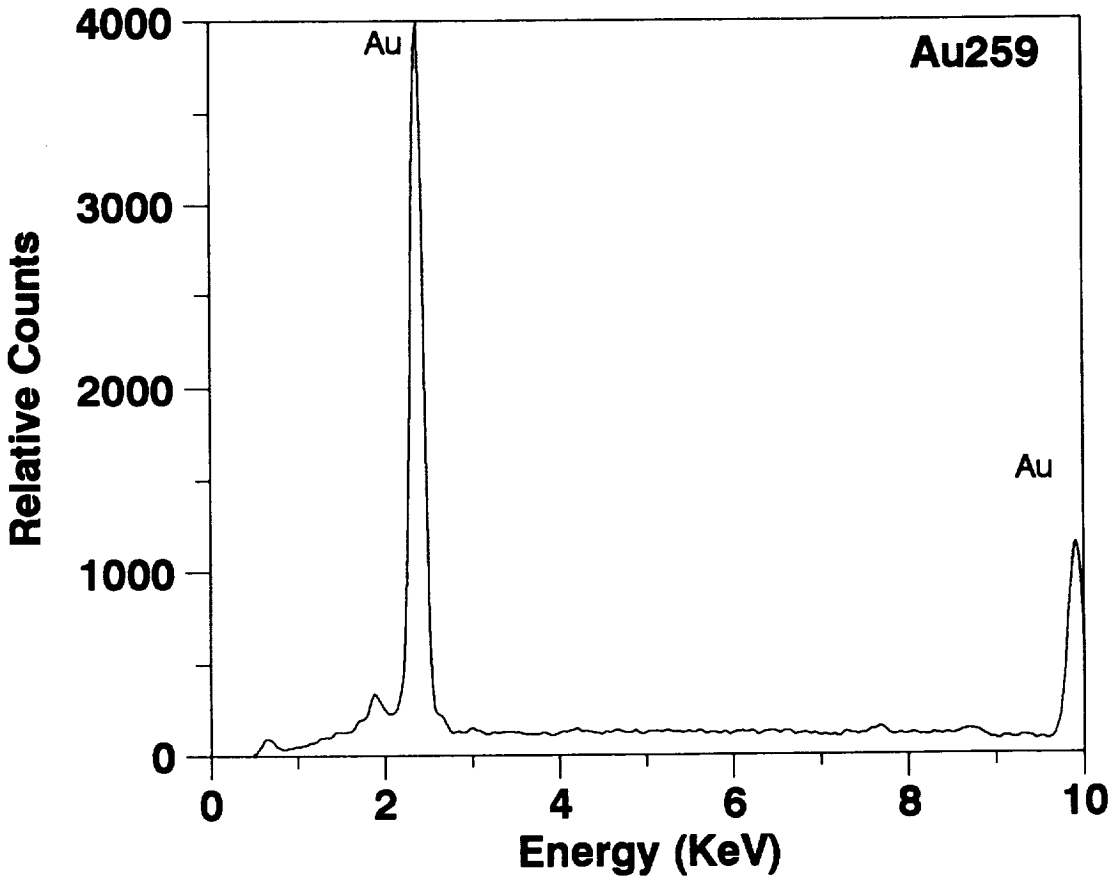


COMPONENT: EOOJ
FEATURE: 259
CORE: LD-212

DIAMETER: 50 μm
ORIGIN: Unknown



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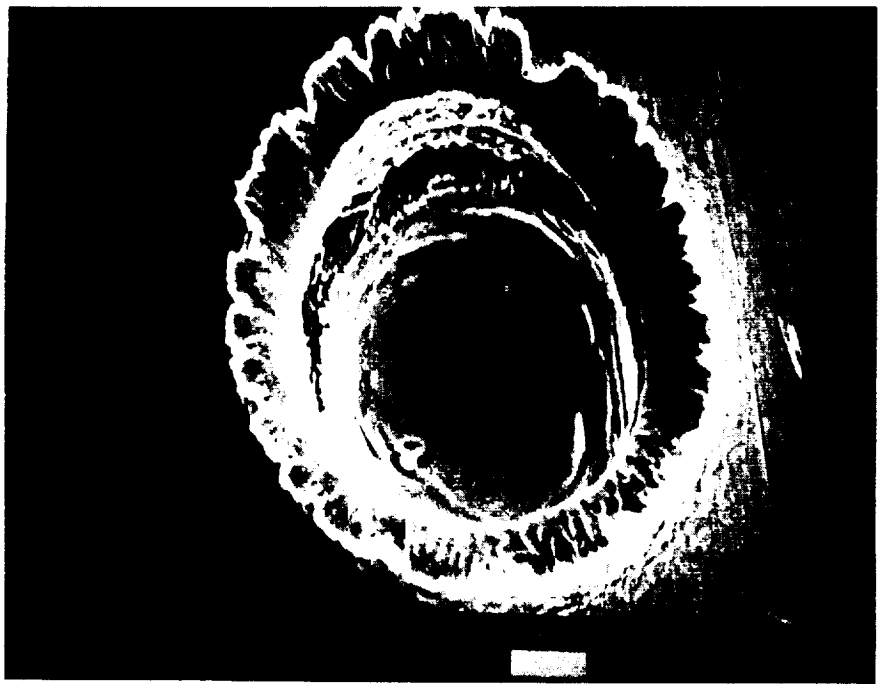
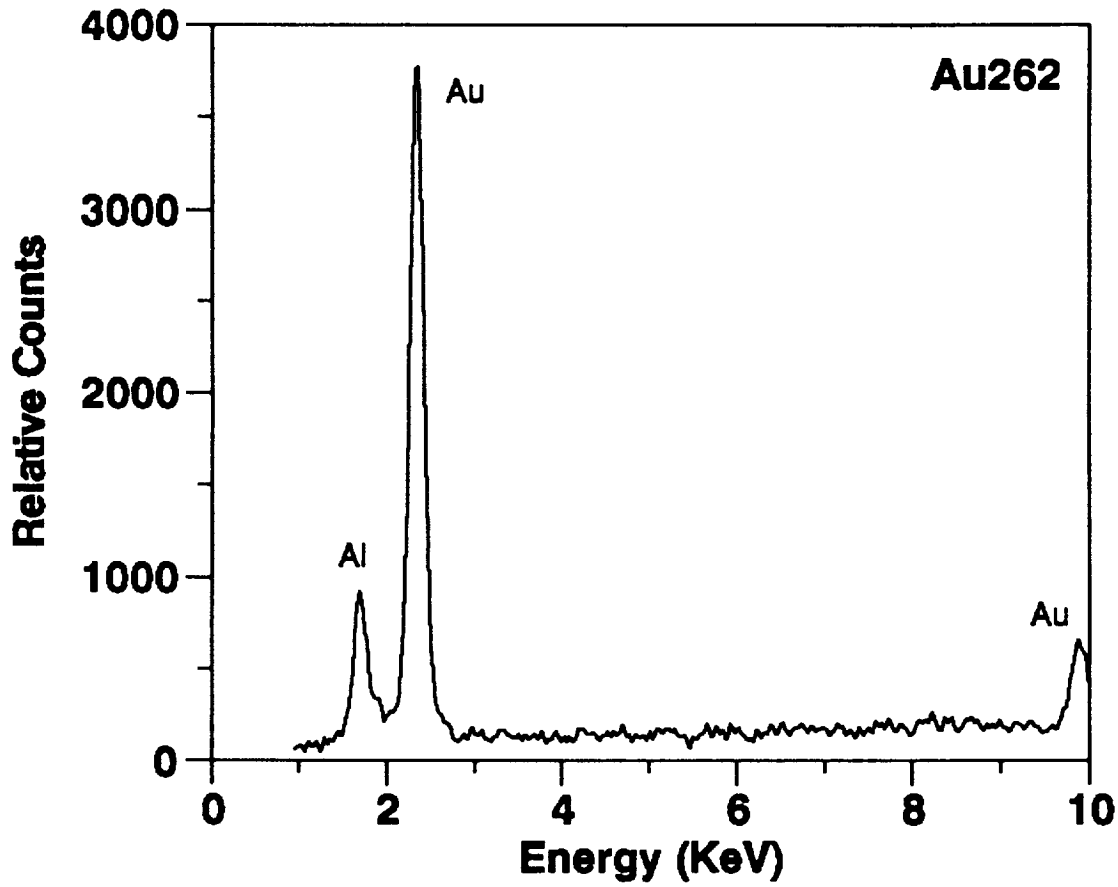


COMPONENT: EOOJ
FEATURE: 262
CORE: LD-214

DIAMETER: 30 μm
ORIGIN: Man-made



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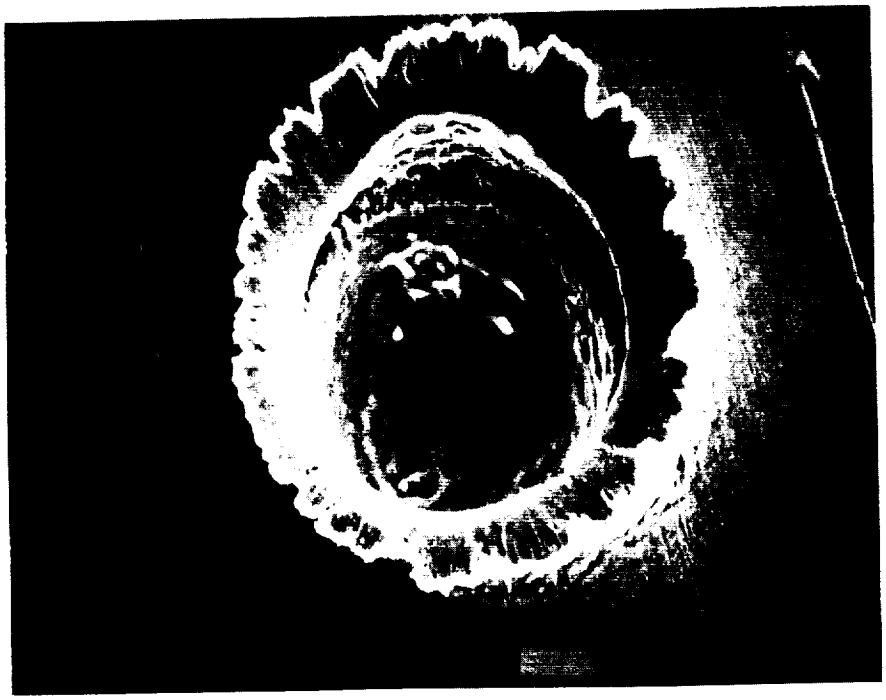
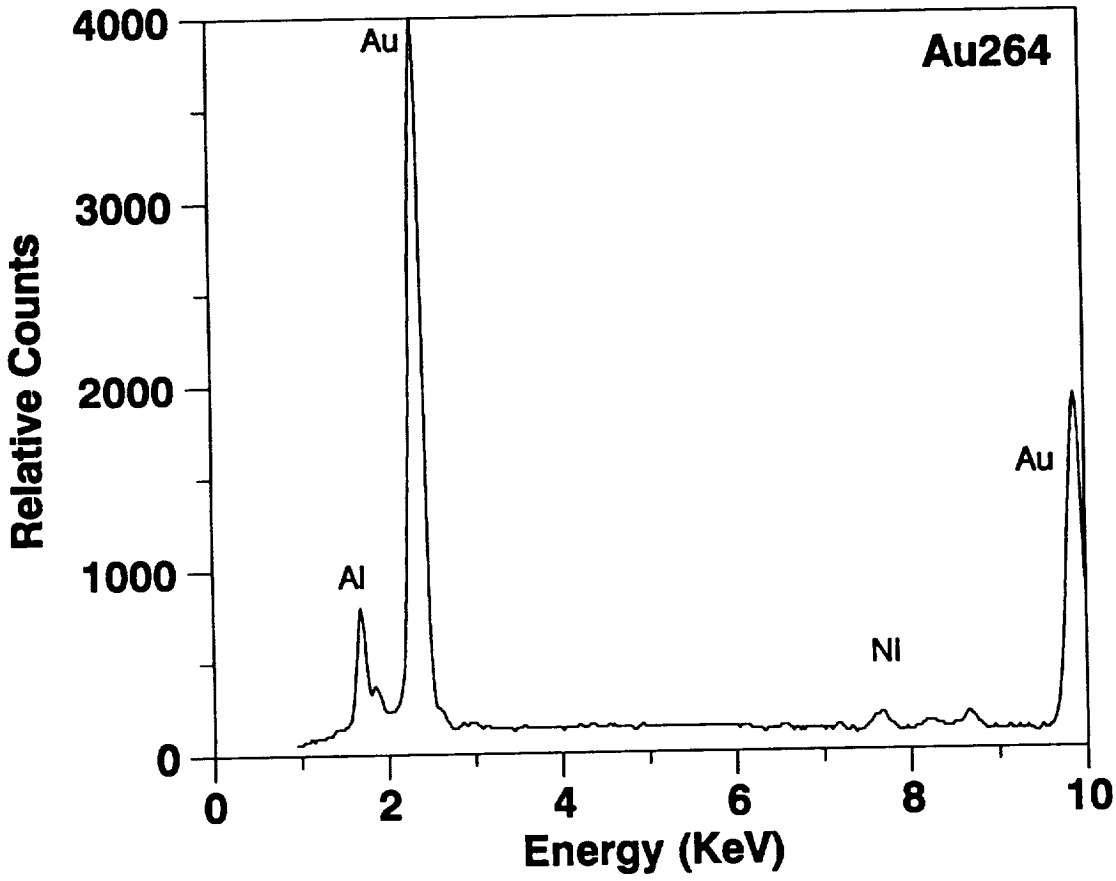


COMPONENT: EOOJ
FEATURE: 264
CORE: LD-216

DIAMETER: 30 μm
ORIGIN: Man-made



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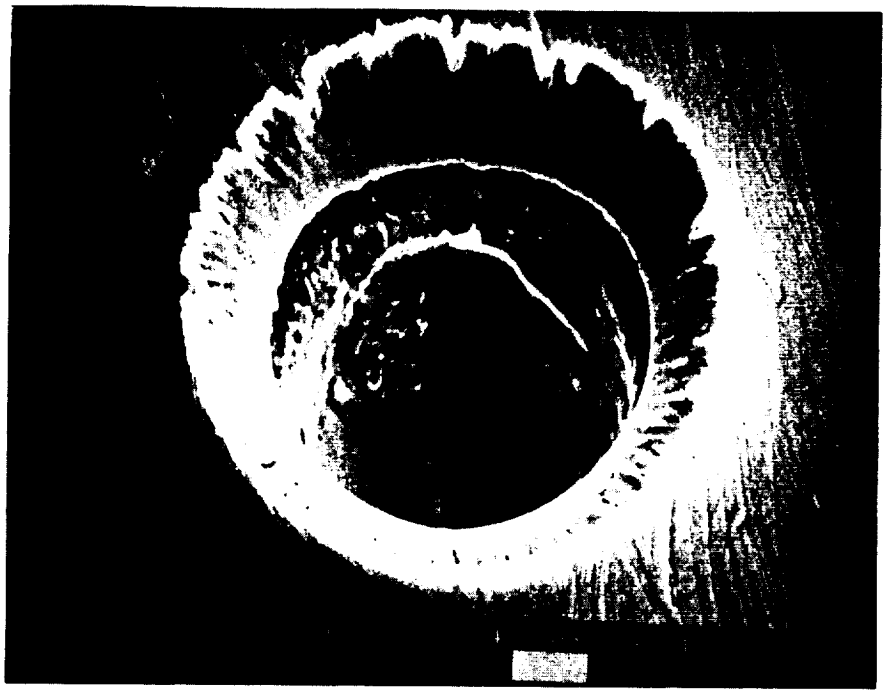
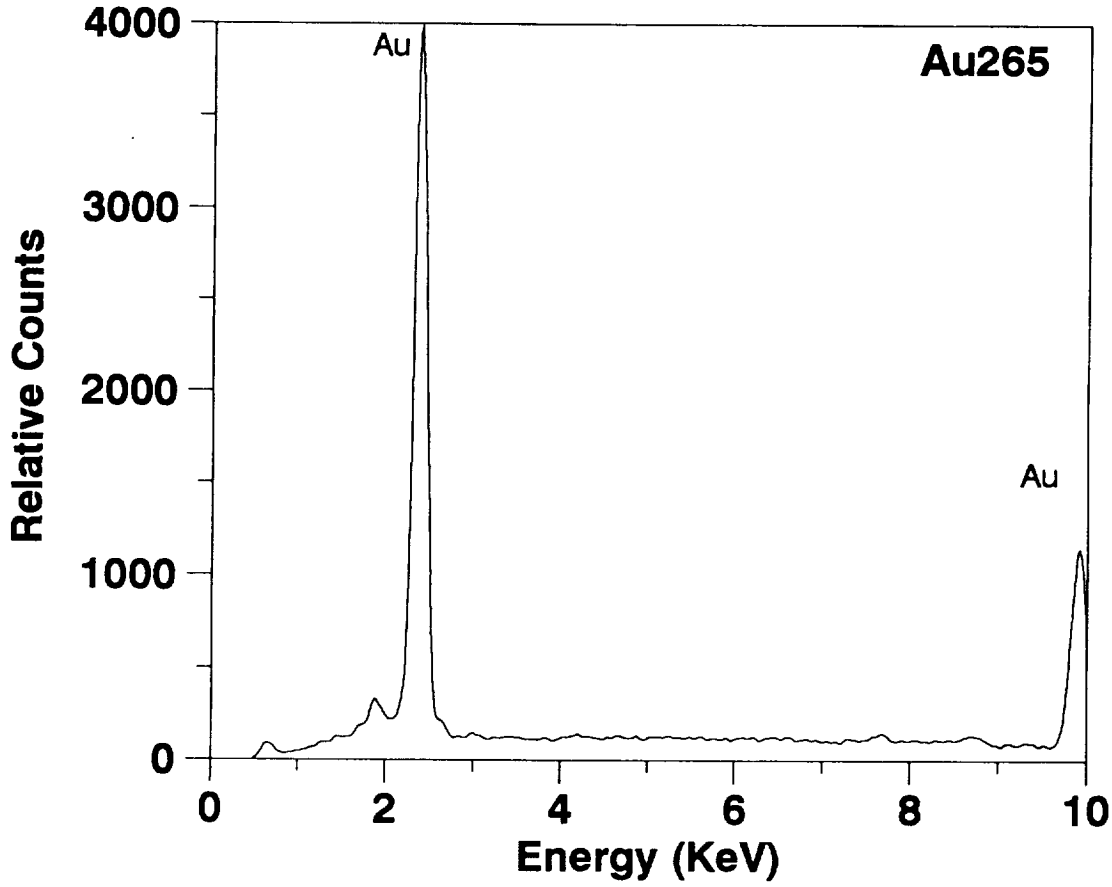


COMPONENT: EOOJ
FEATURE: 265
CORE: LD-218

DIAMETER: 25 μm
ORIGIN: Unknown



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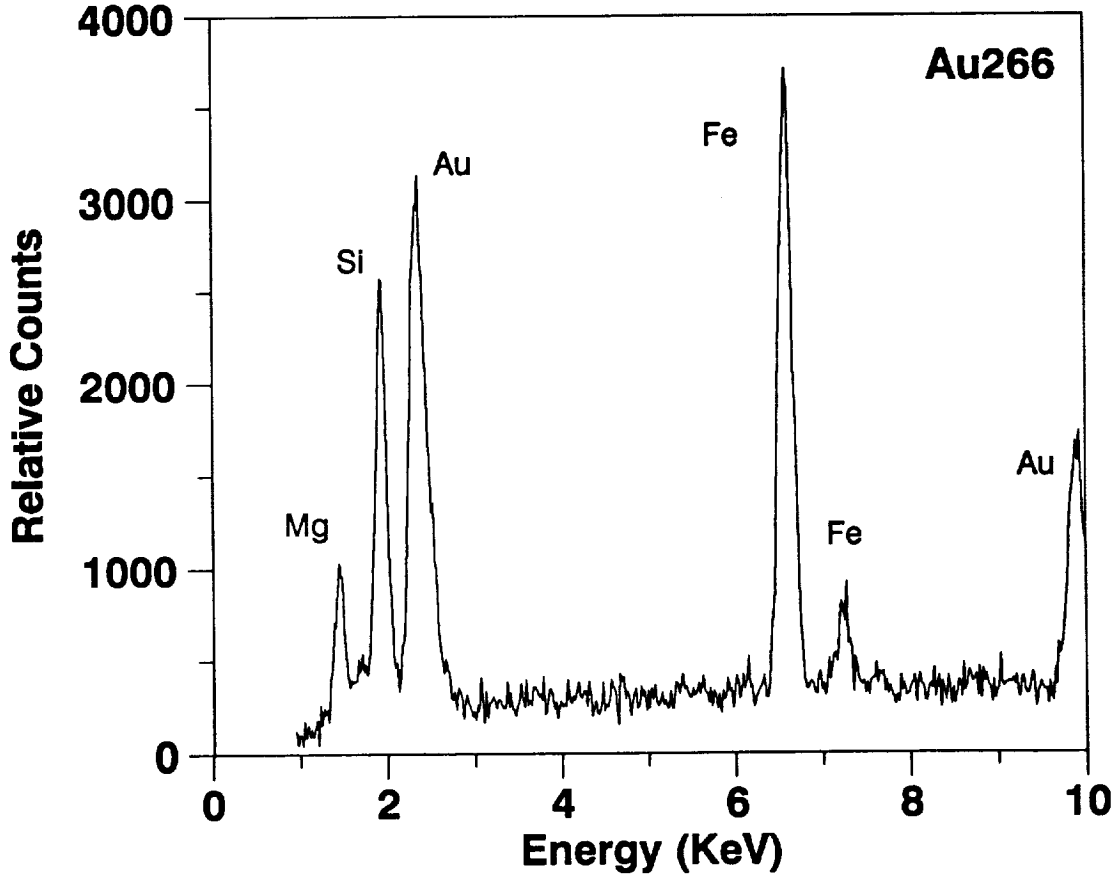
COMPONENT: EOOJ
FEATURE: 266
CORE: LD-217

DIAMETER: 460 μm
ORIGIN: Natural



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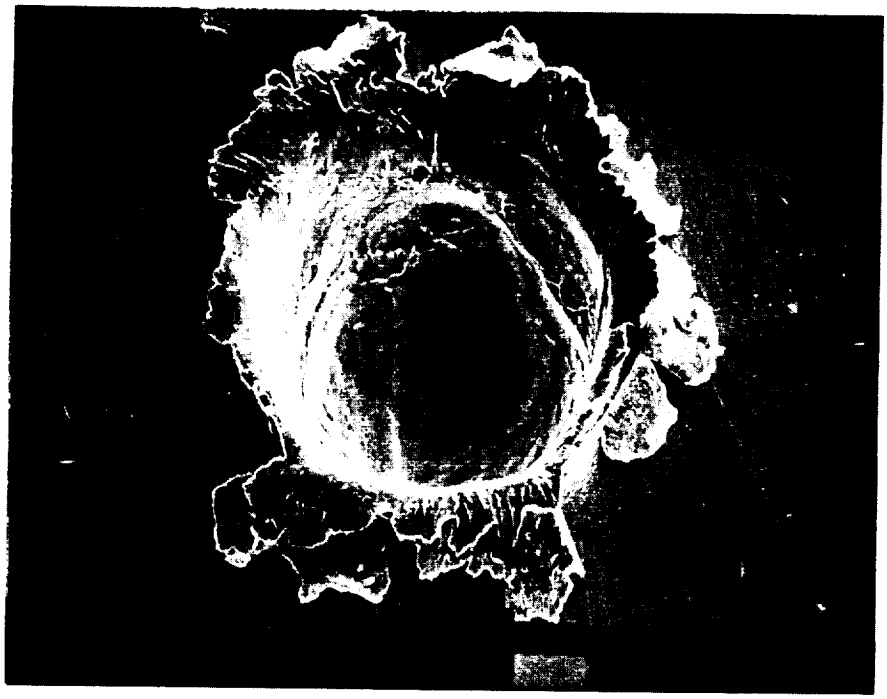
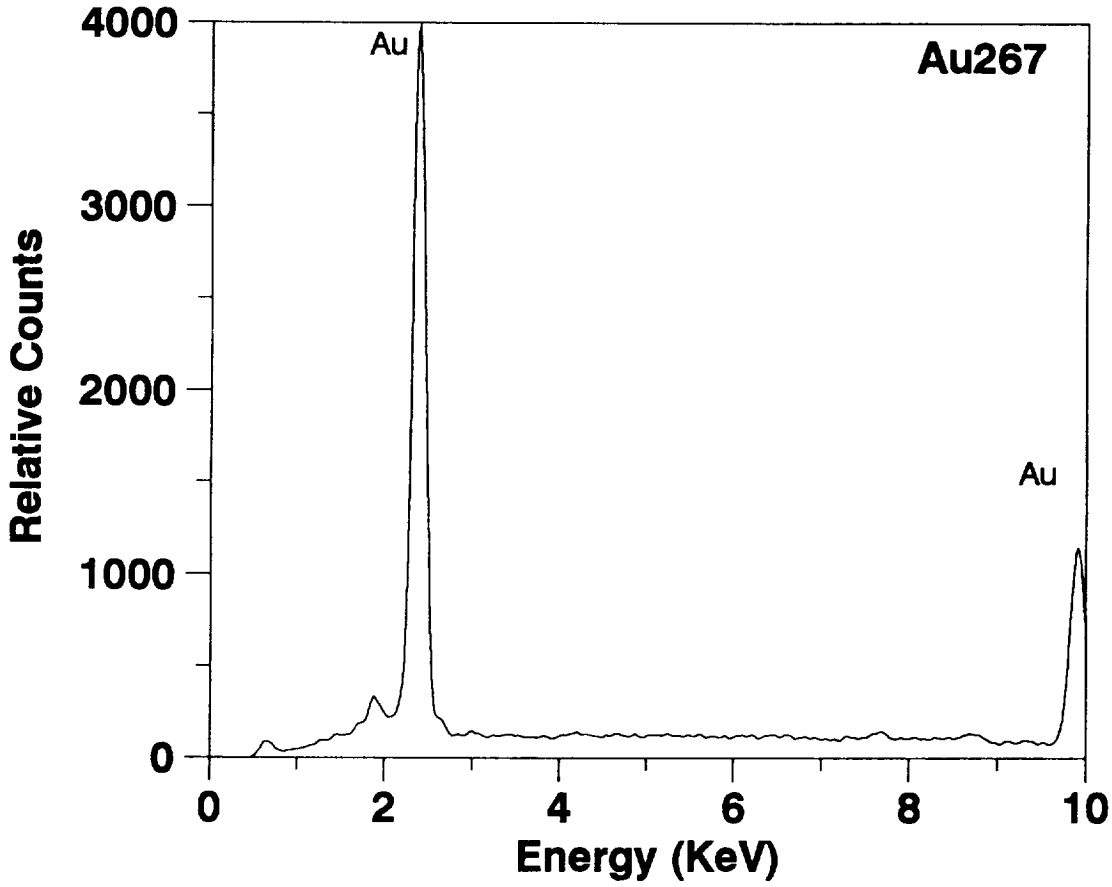


COMPONENT: EOOJ
FEATURE: 267
CORE: LD-219

DIAMETER: 115 μm
ORIGIN: Unknown



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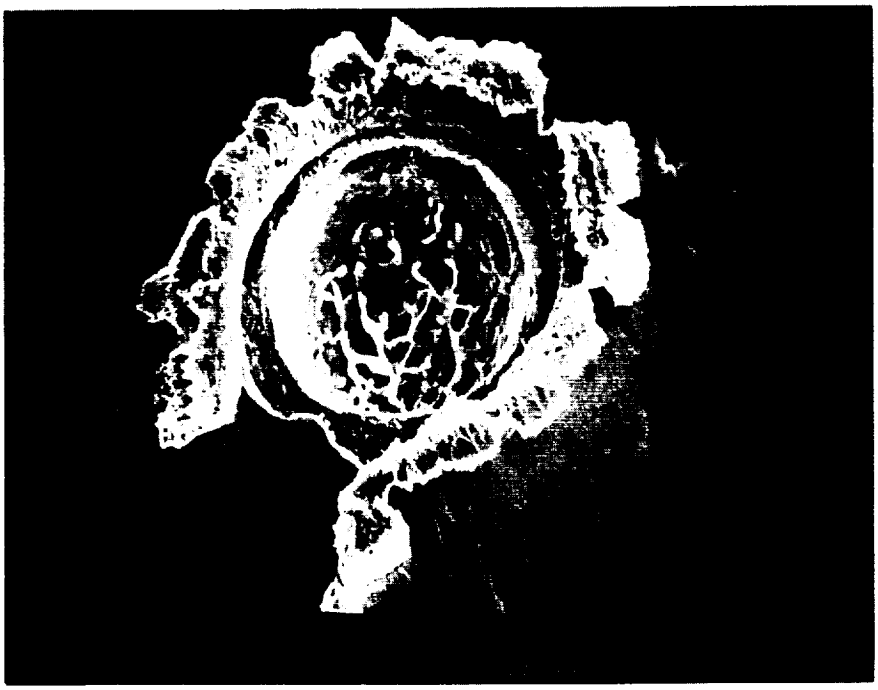
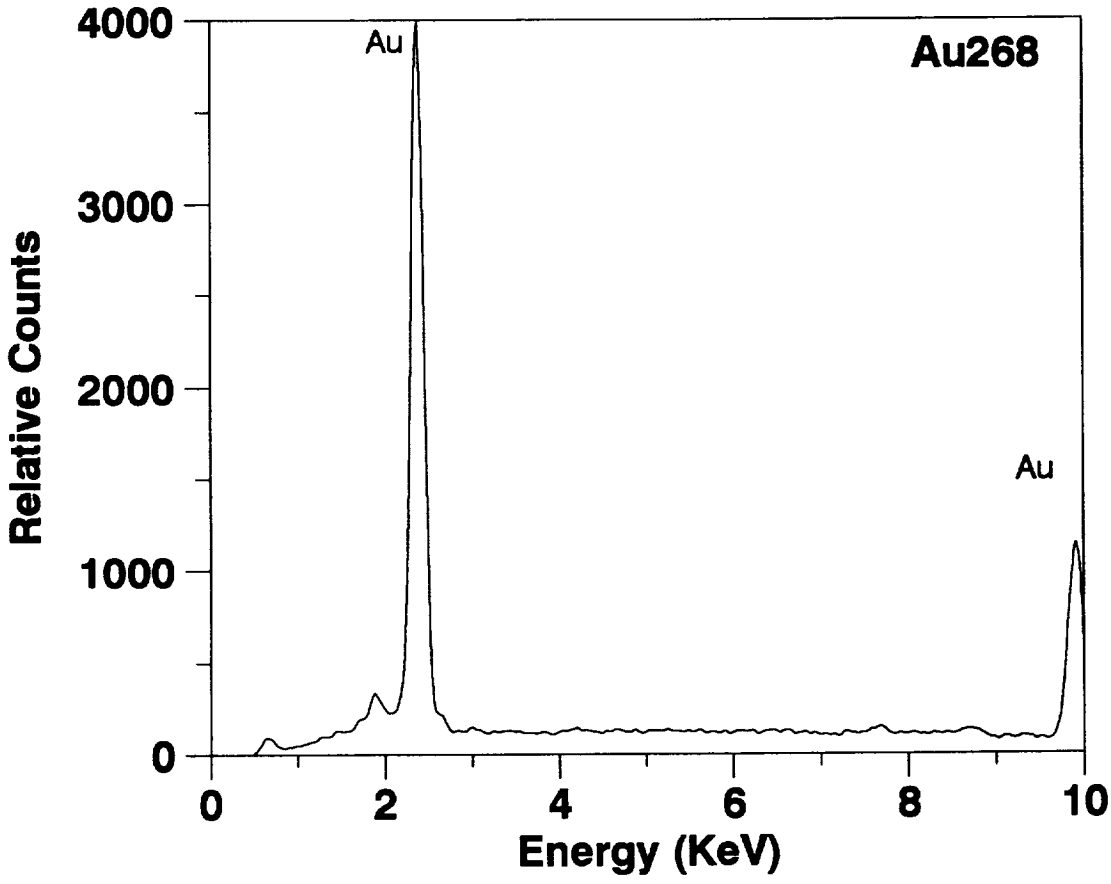


COMPONENT: EOOJ
FEATURE: 268
CORE: LD-220

DIAMETER: 40 μm
ORIGIN: Unknown



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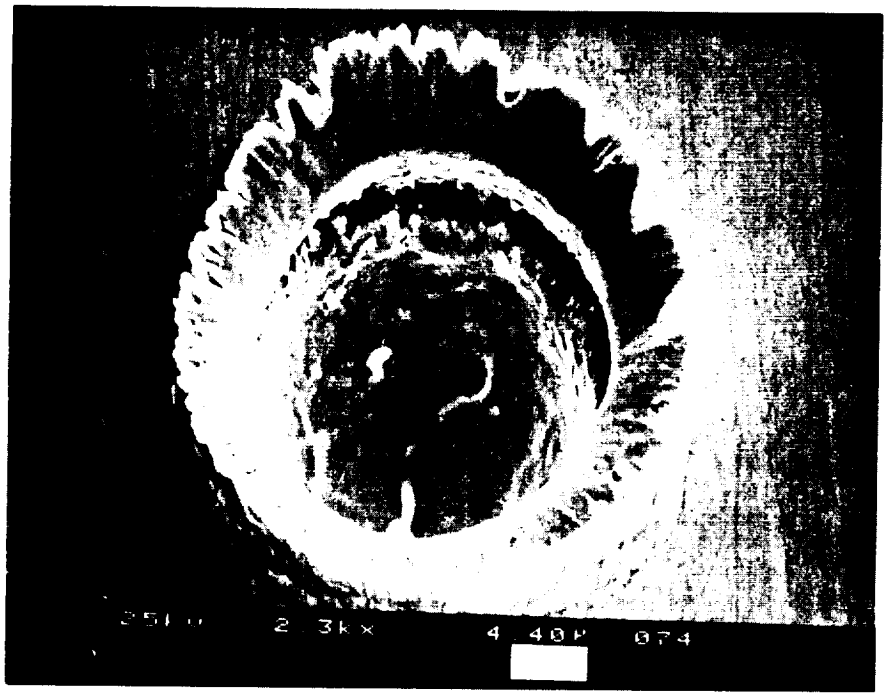
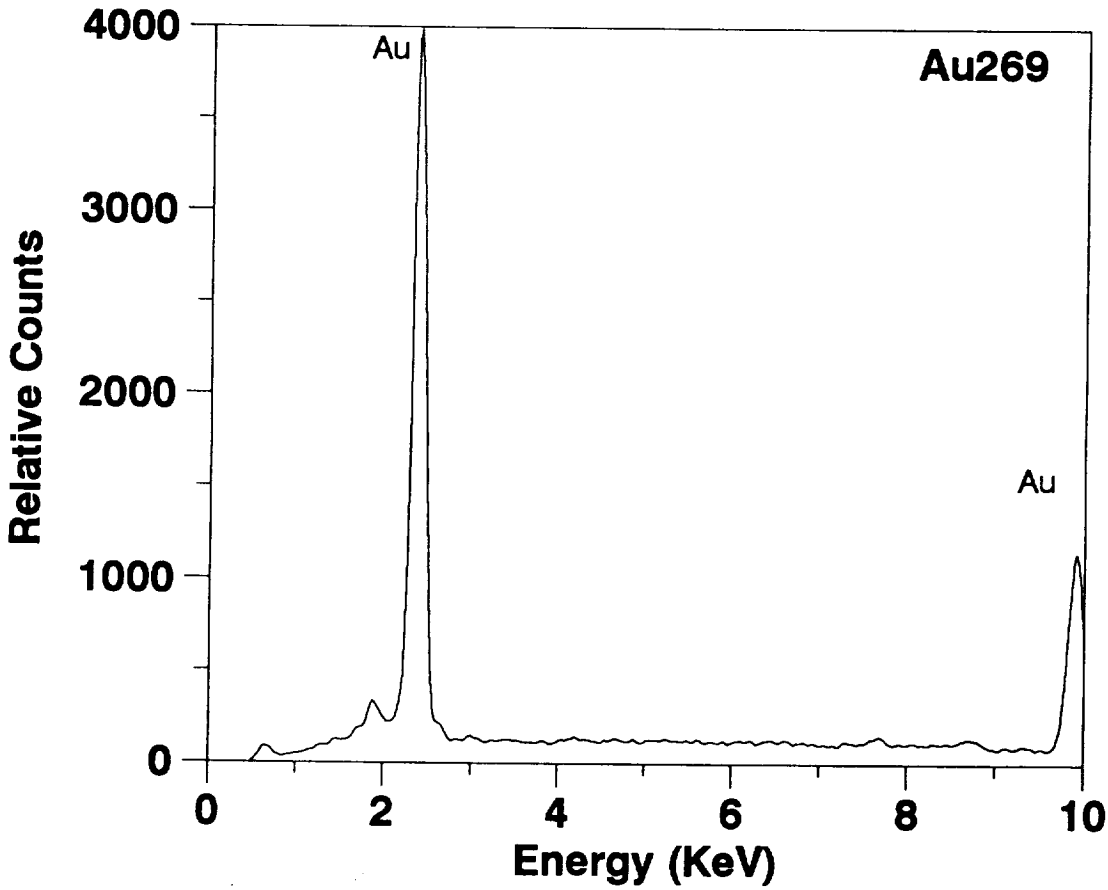


COMPONENT: EOOJ
FEATURE: 269
CORE: LD-221

DIAMETER: 45 μm
ORIGIN: Unknown



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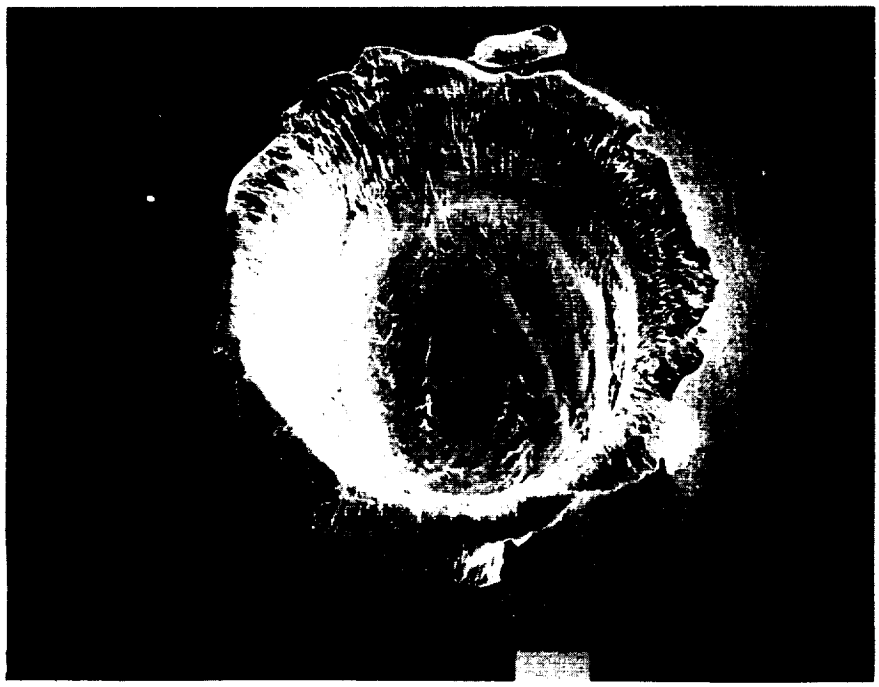
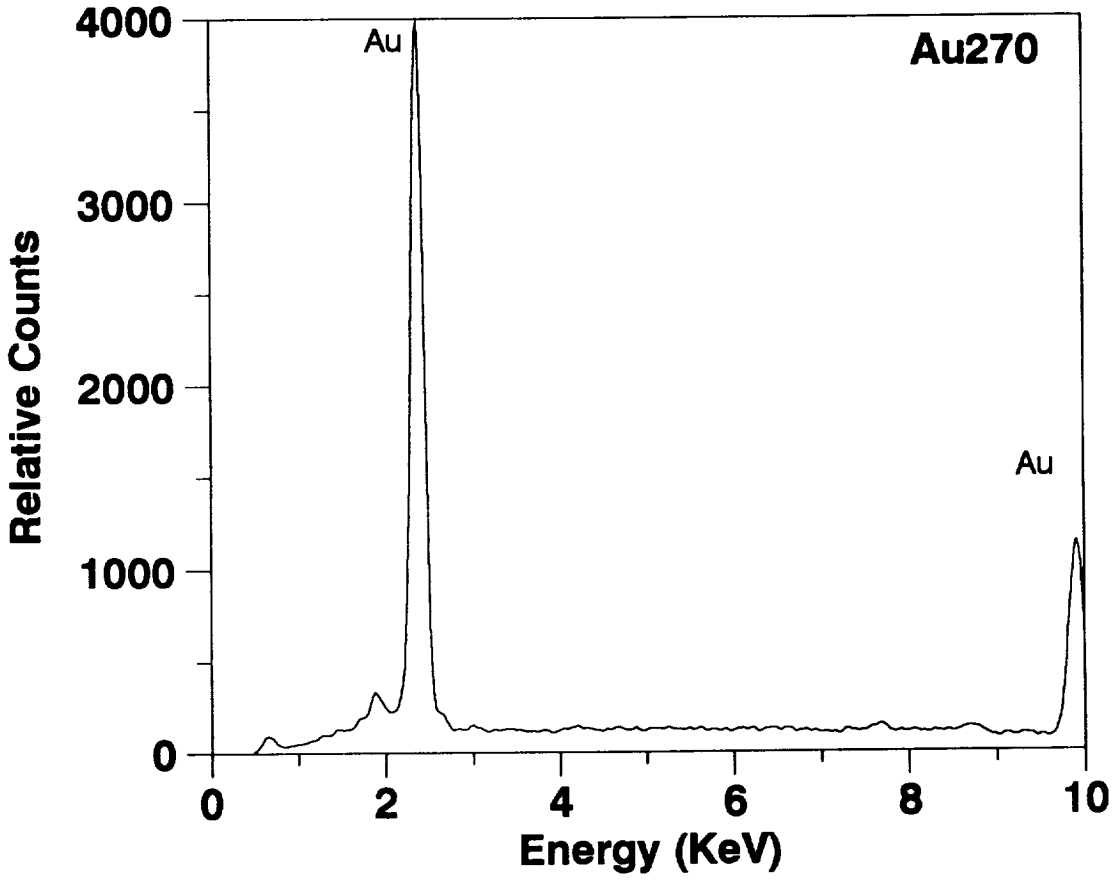


COMPONENT: EOOJ
FEATURE: 270
CORE: LD-222

DIAMETER: 330 μm
ORIGIN: Unknown



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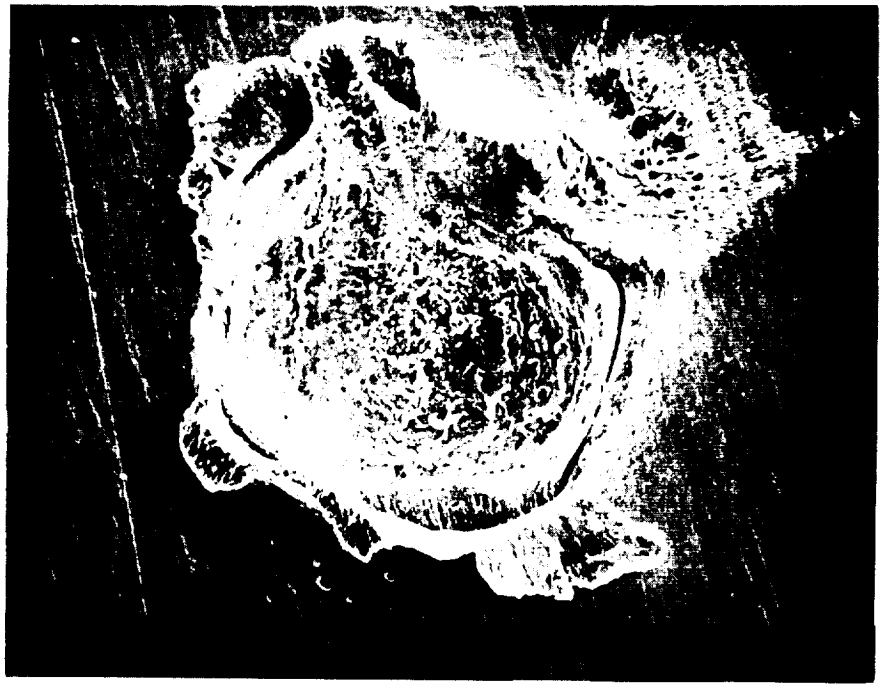
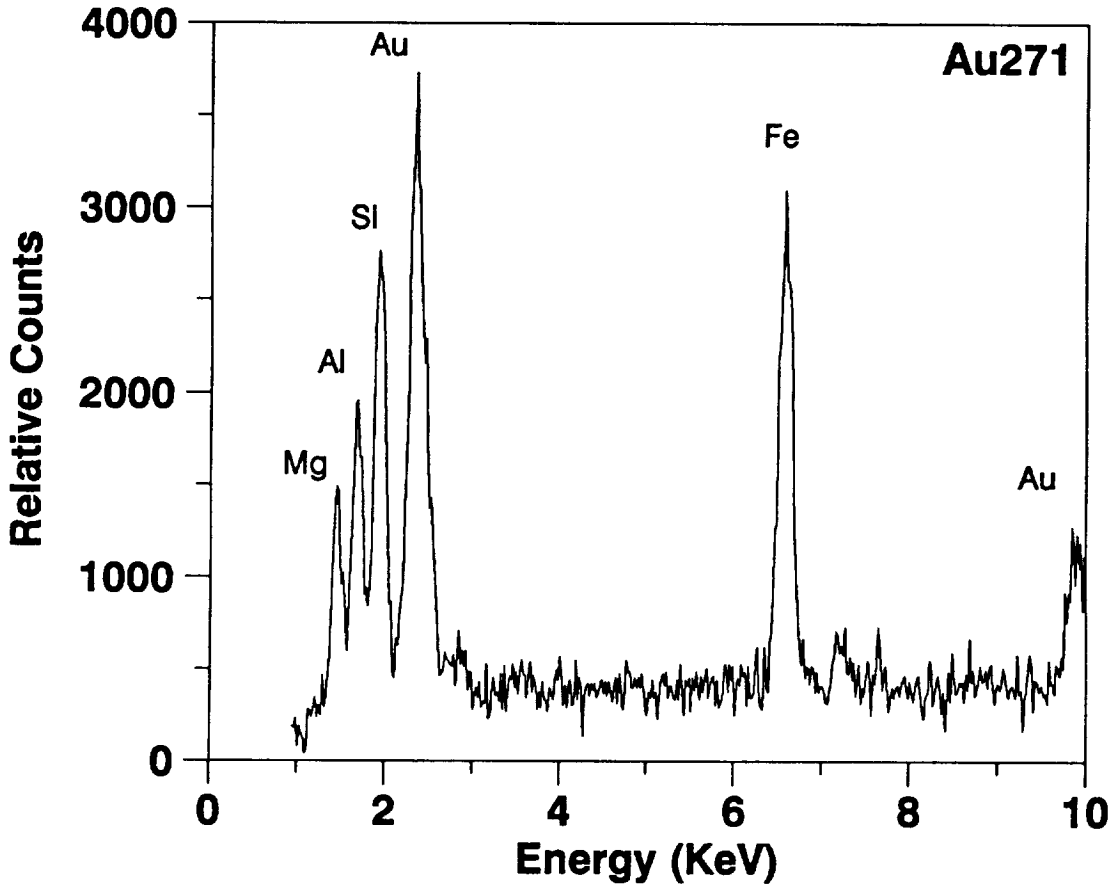


COMPONENT: EOOJ
FEATURE: 271
CORE: LD-233

DIAMETER: 60 μm
ORIGIN: Natural



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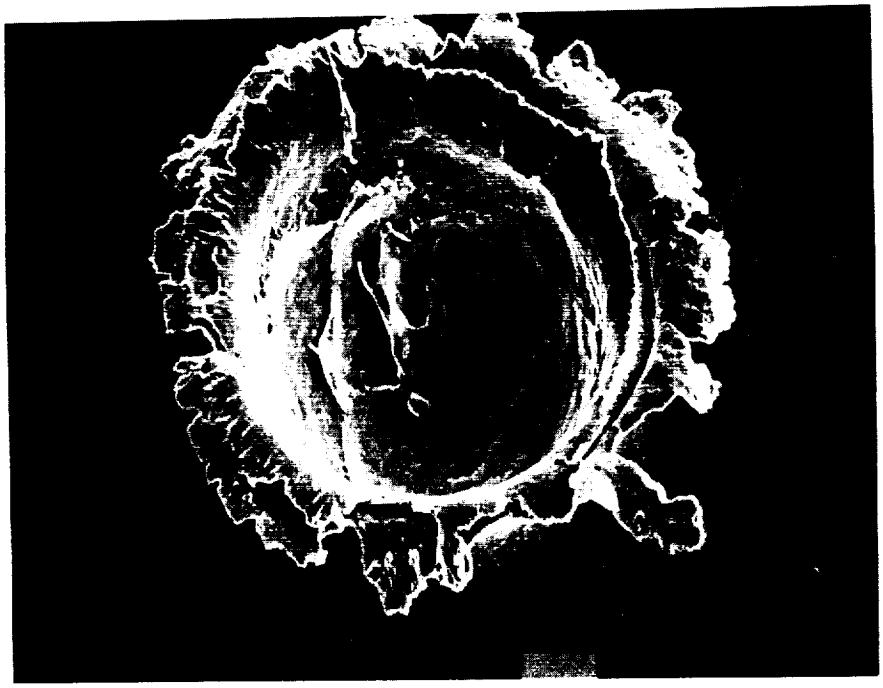
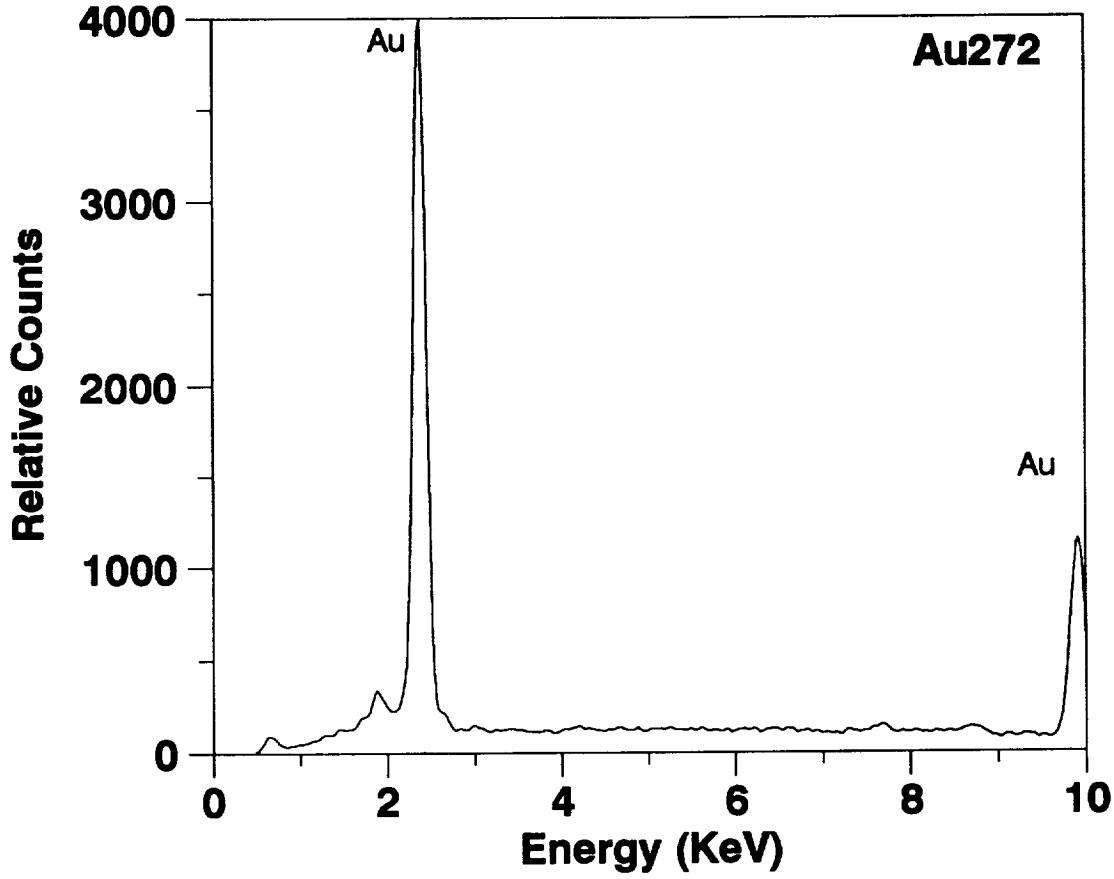


COMPONENT: EOOJ
FEATURE: 272
CORE: LD-224

DIAMETER: 65 μm
ORIGIN: Unknown



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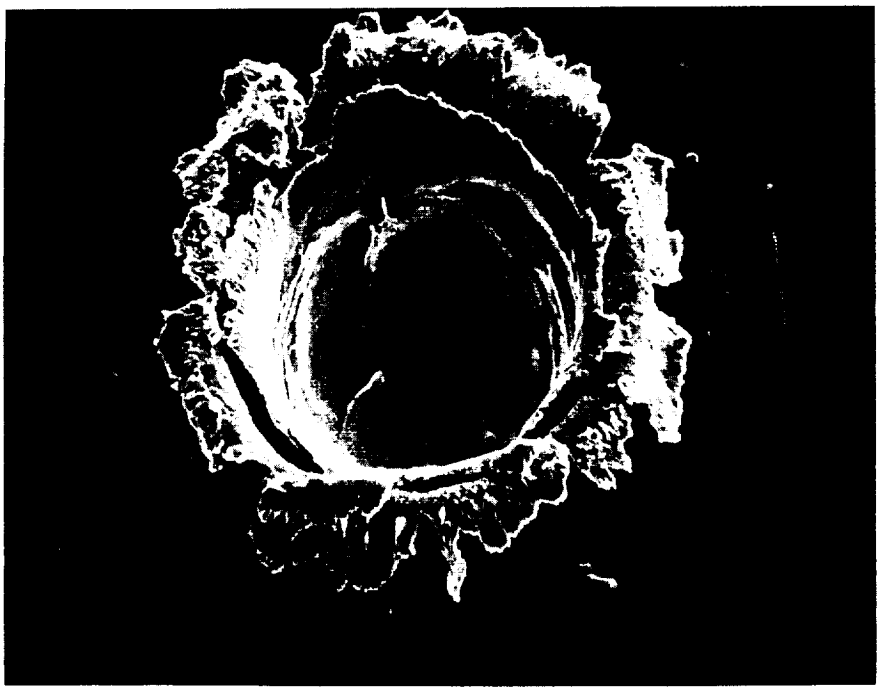
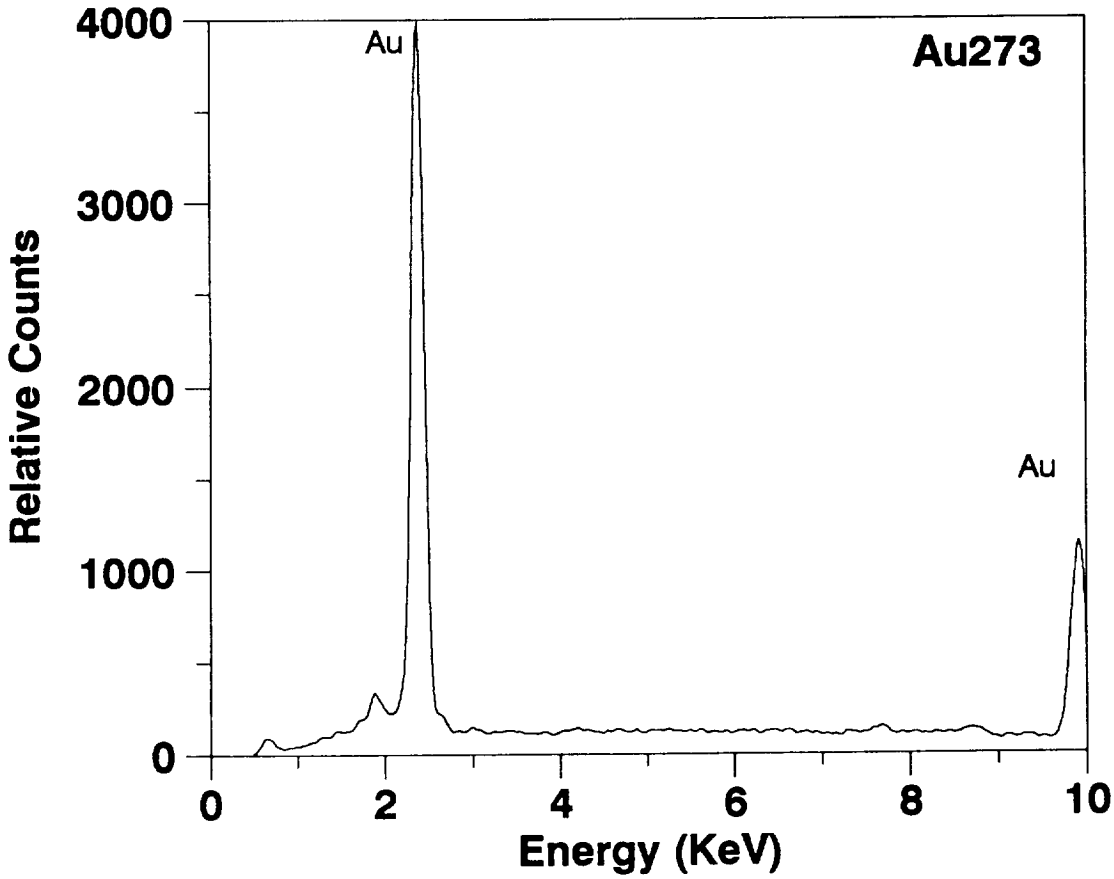


COMPONENT: EOOJ
FEATURE: 273
CORE: LD-225

DIAMETER: 55 μm
ORIGIN: Unknown



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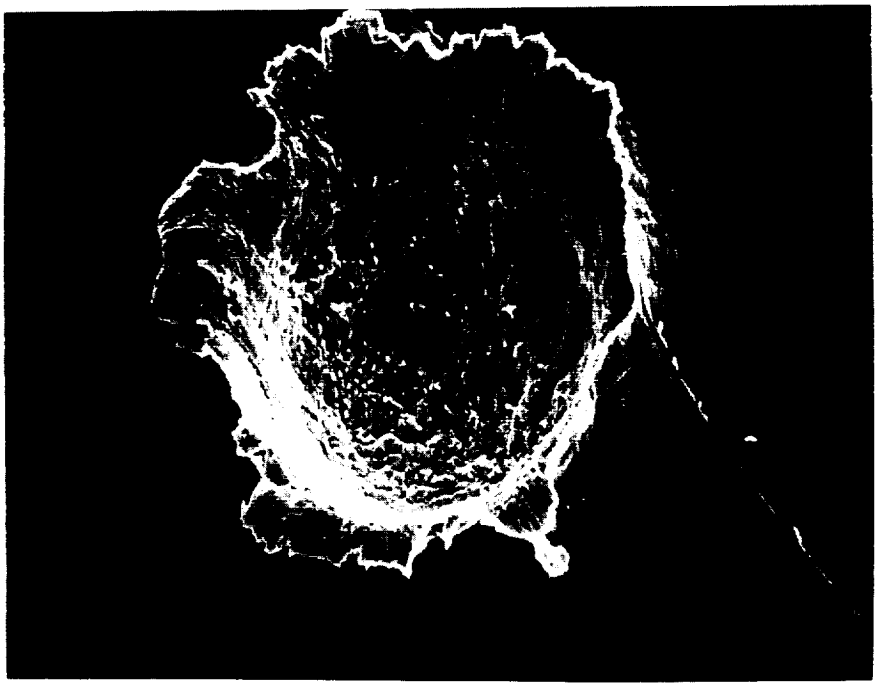
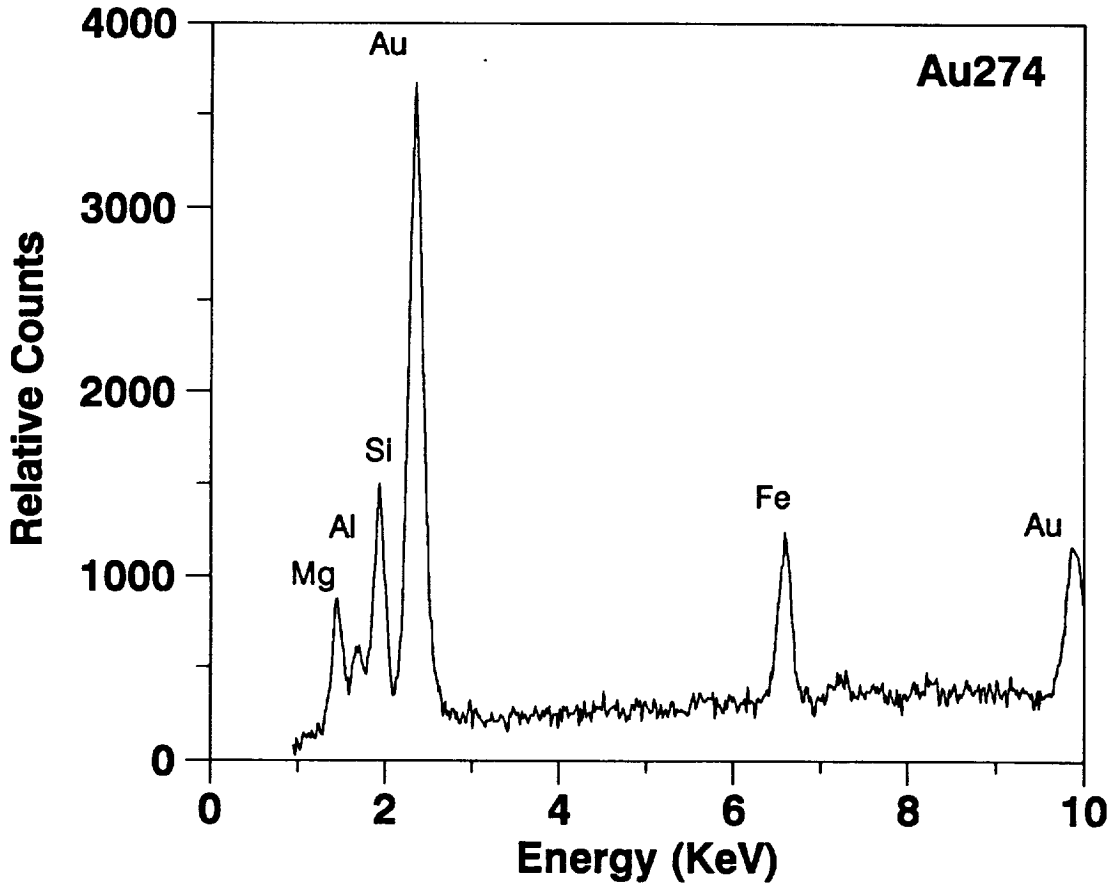


COMPONENT: EOOK
FEATURE: 274
CORE: LD-259

DIAMETER: 45 μm
ORIGIN: Natural



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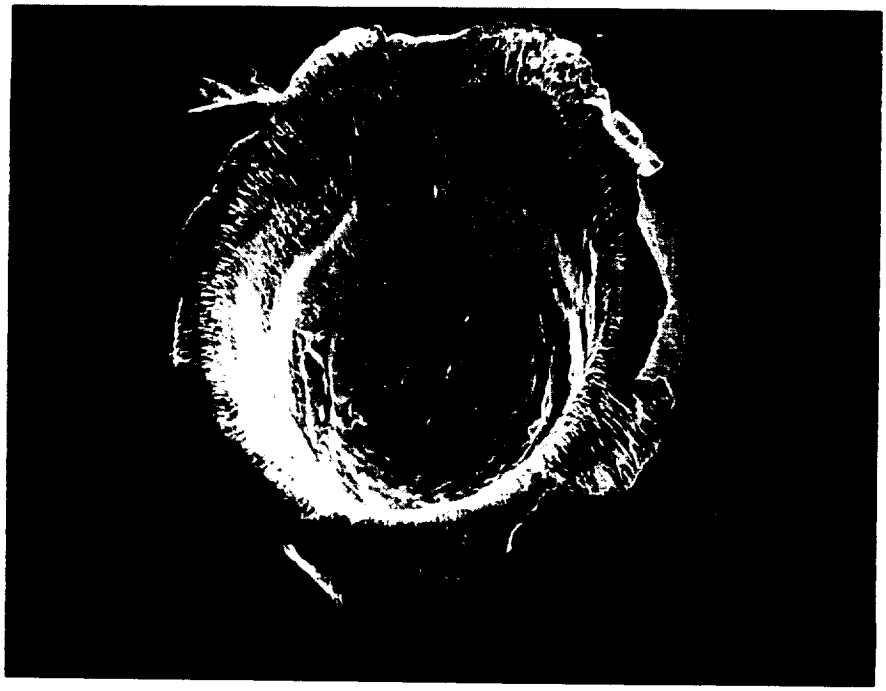
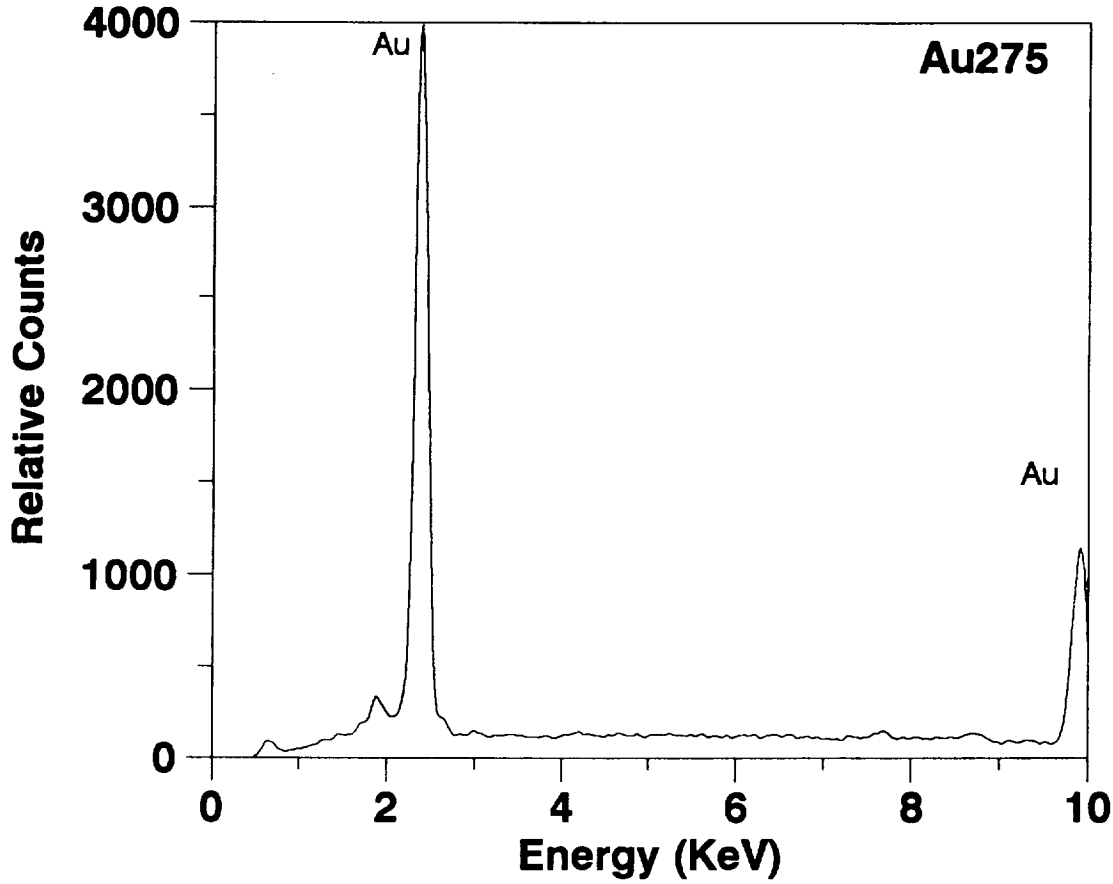


COMPONENT: EOOK
FEATURE: 275
CORE: LD-260

DIAMETER: 485 μm
ORIGIN: Unknown



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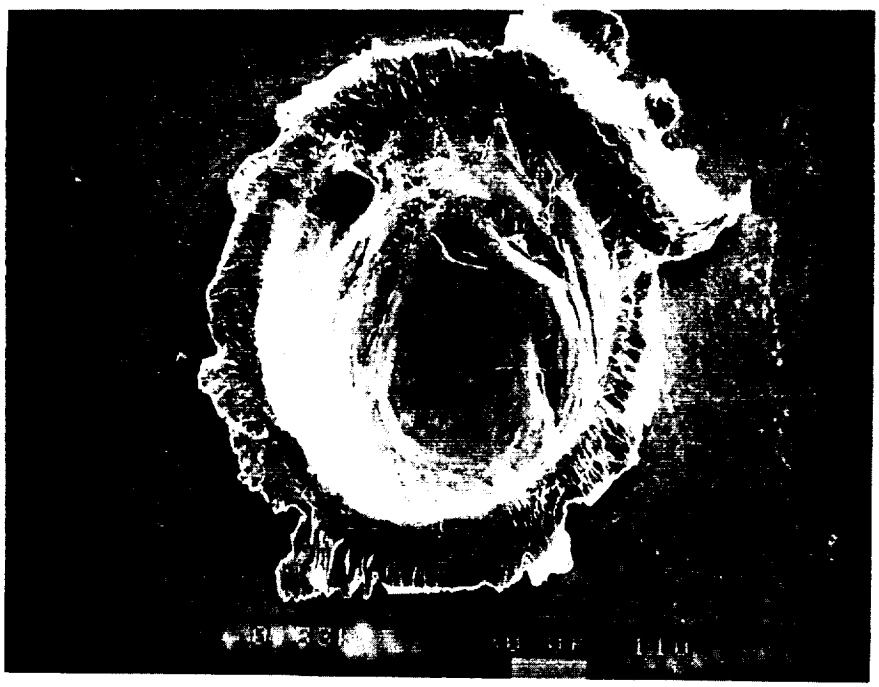
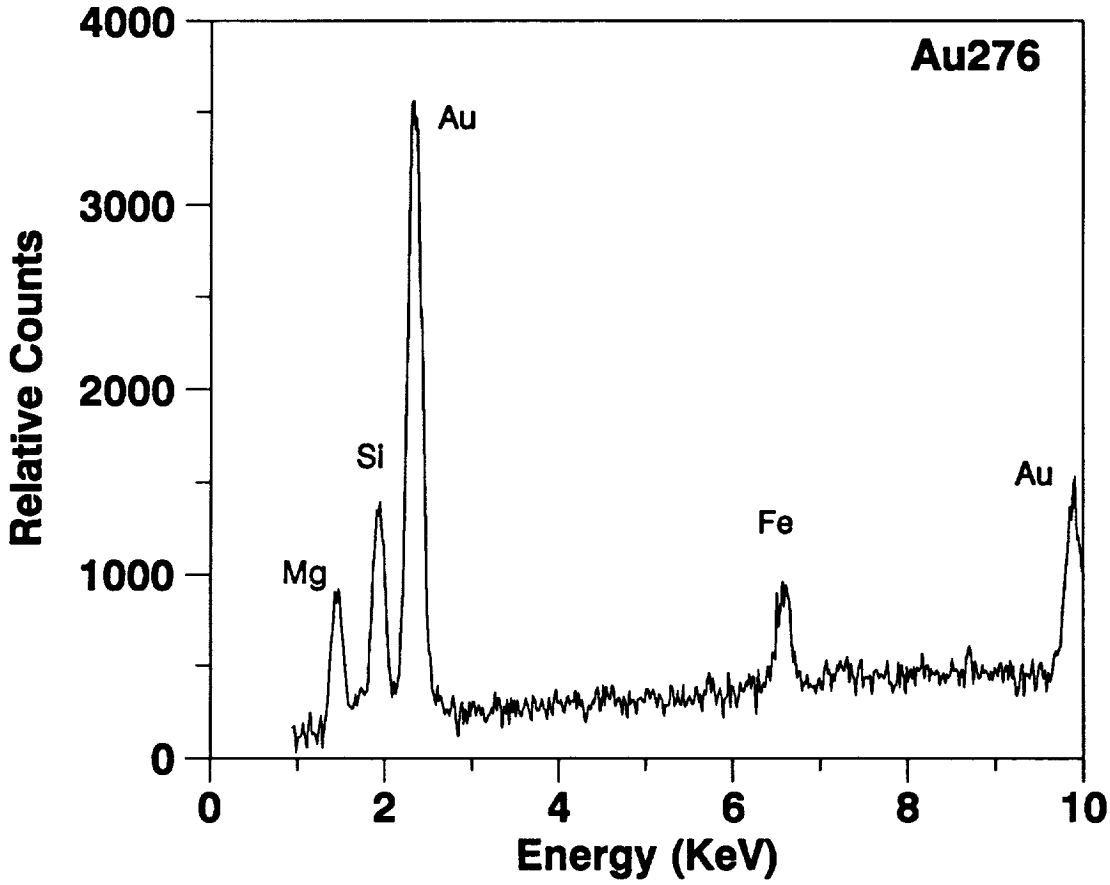


COMPONENT: EOOK
FEATURE: 276
CORE: LD-261

DIAMETER: 170 μm
ORIGIN: Natural



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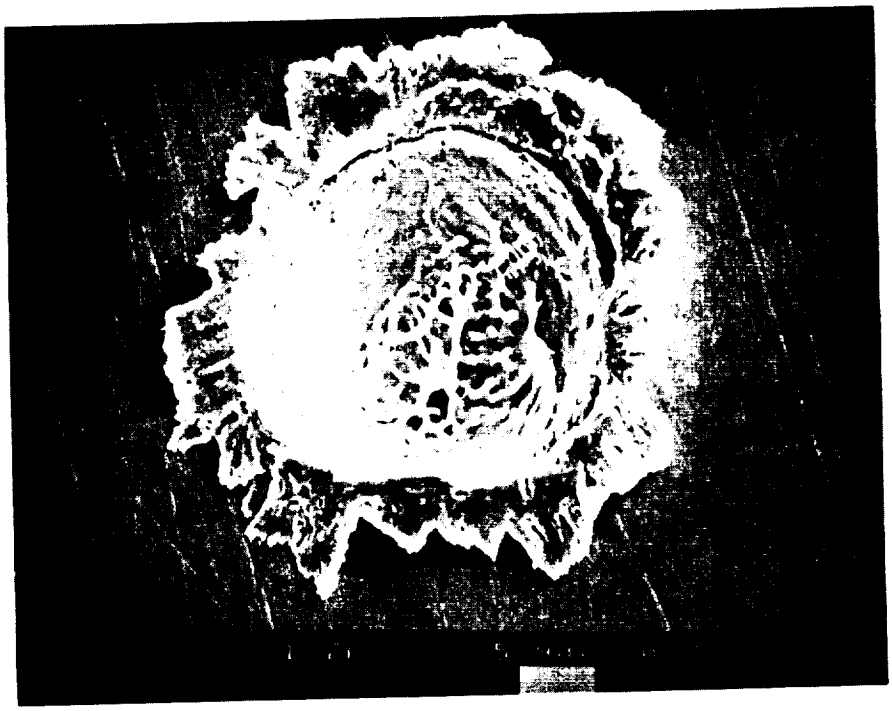
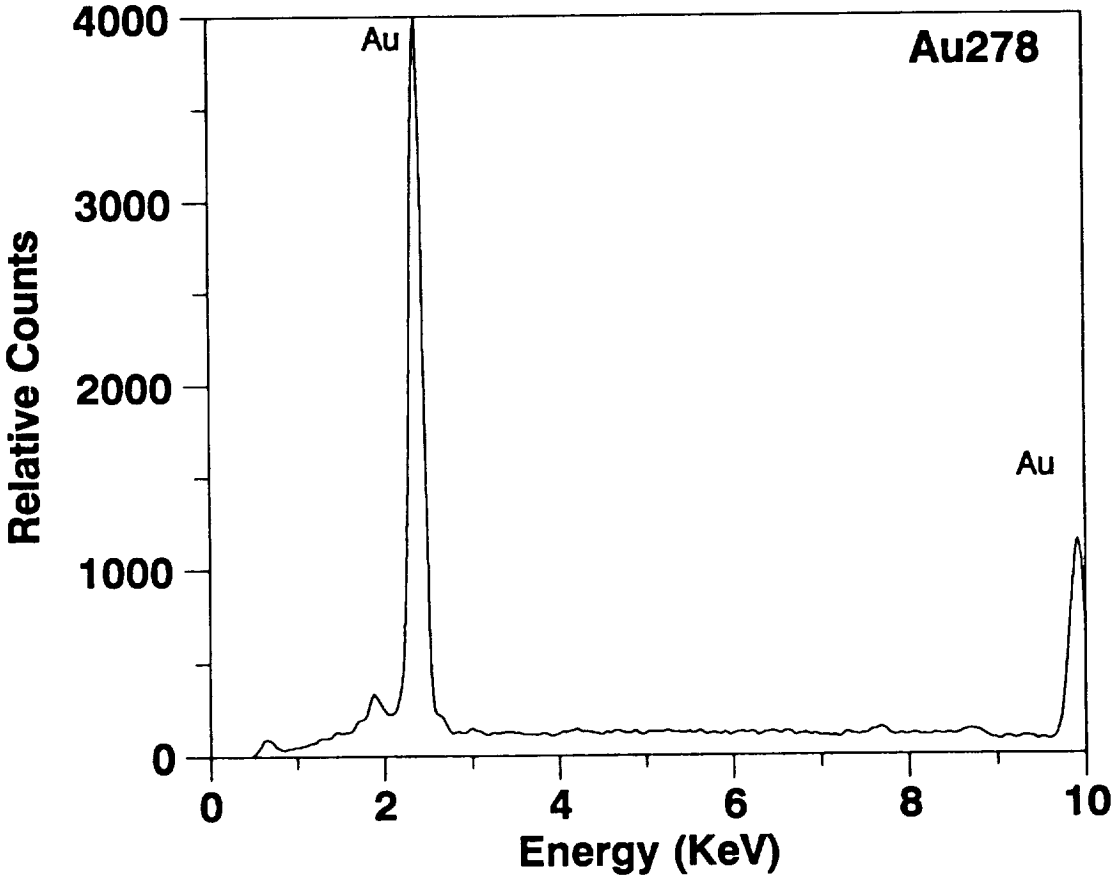


COMPONENT: EOOK
FEATURE: 278
CORE: LD-232

DIAMETER: 30 μm
ORIGIN: Unknown



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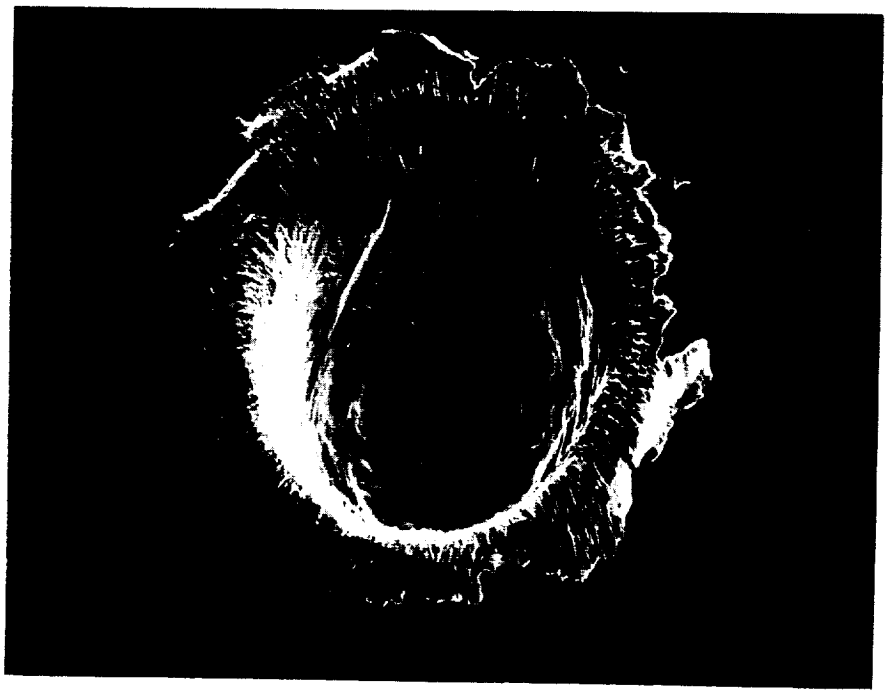
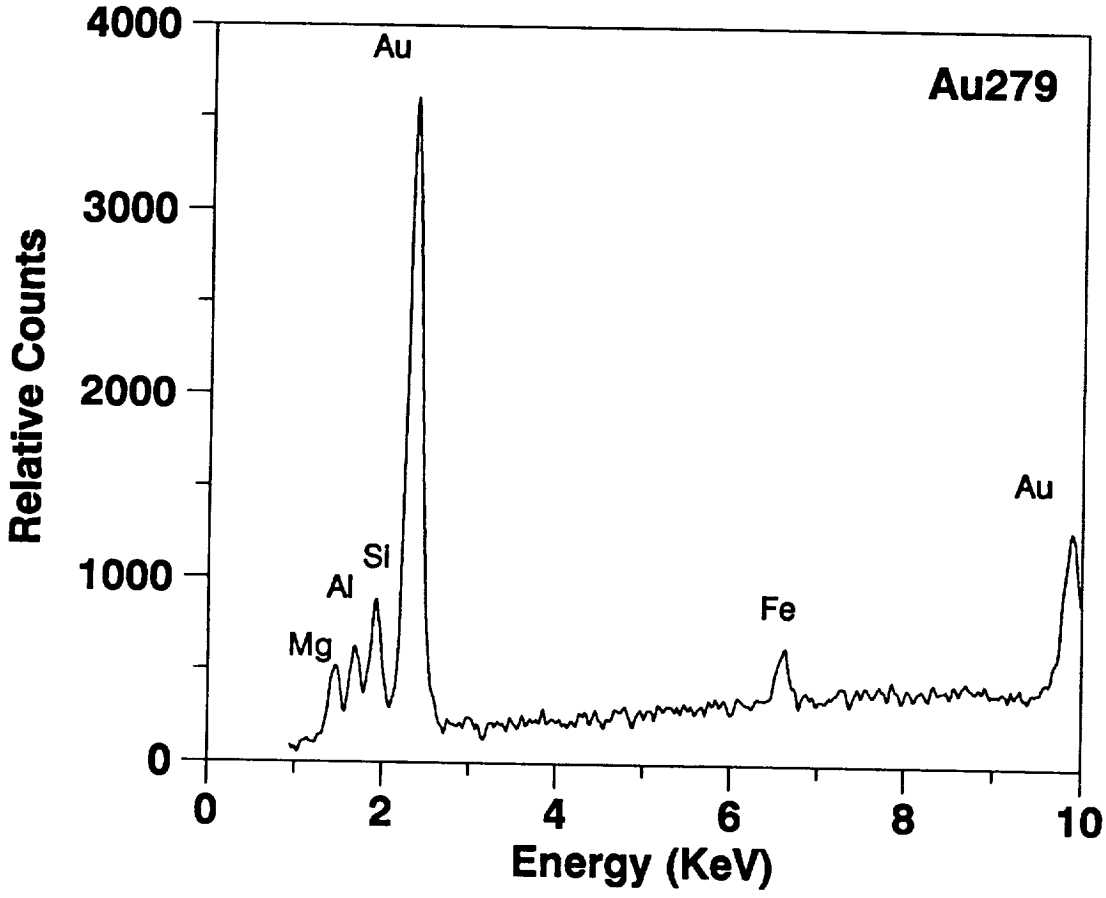


COMPONENT: EOOK
FEATURE: 279
CORE: LD-233

DIAMETER: 220 μm
ORIGIN: Natural



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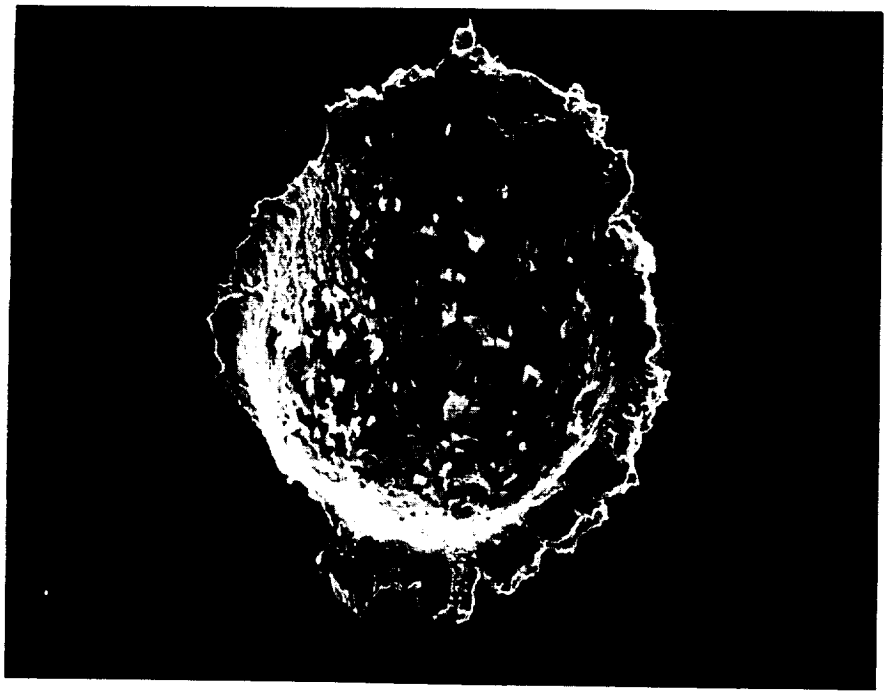
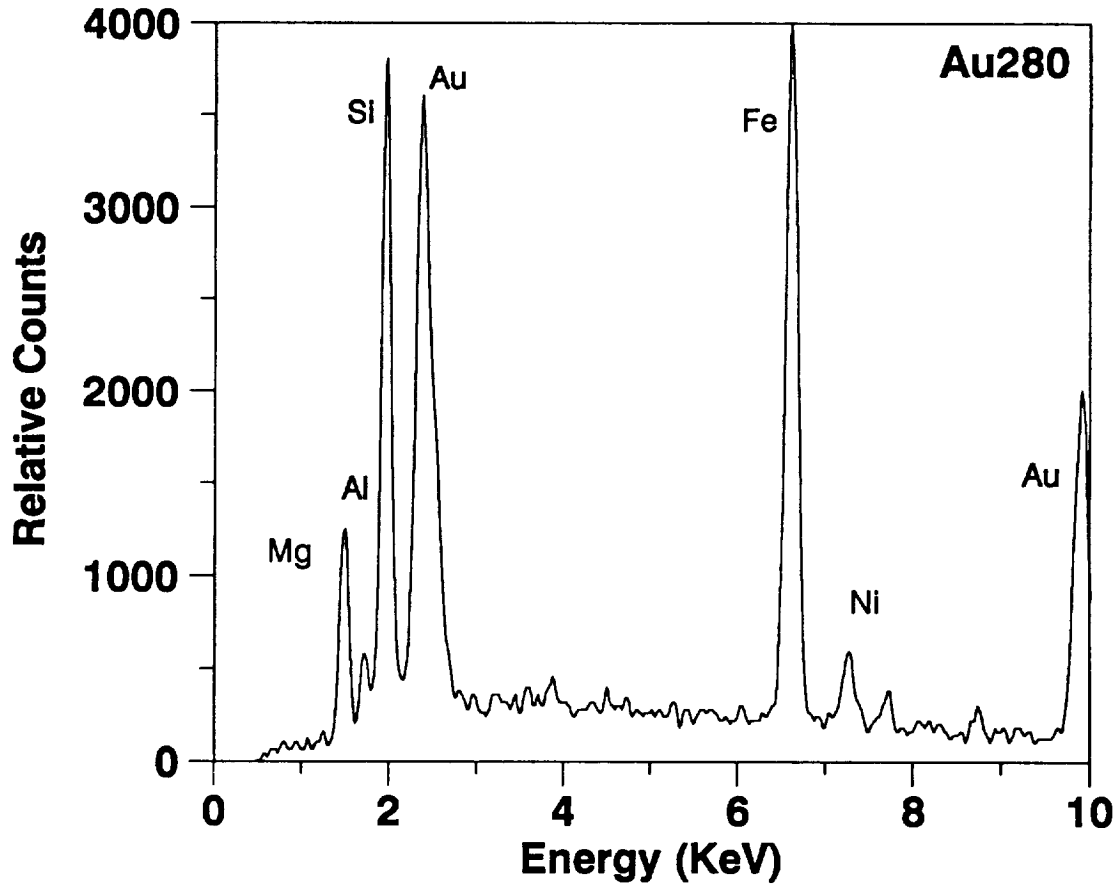


COMPONENT: EOOK
FEATURE: 280
CORE: LD-234

DIAMETER: 160 μm
ORIGIN: Natural



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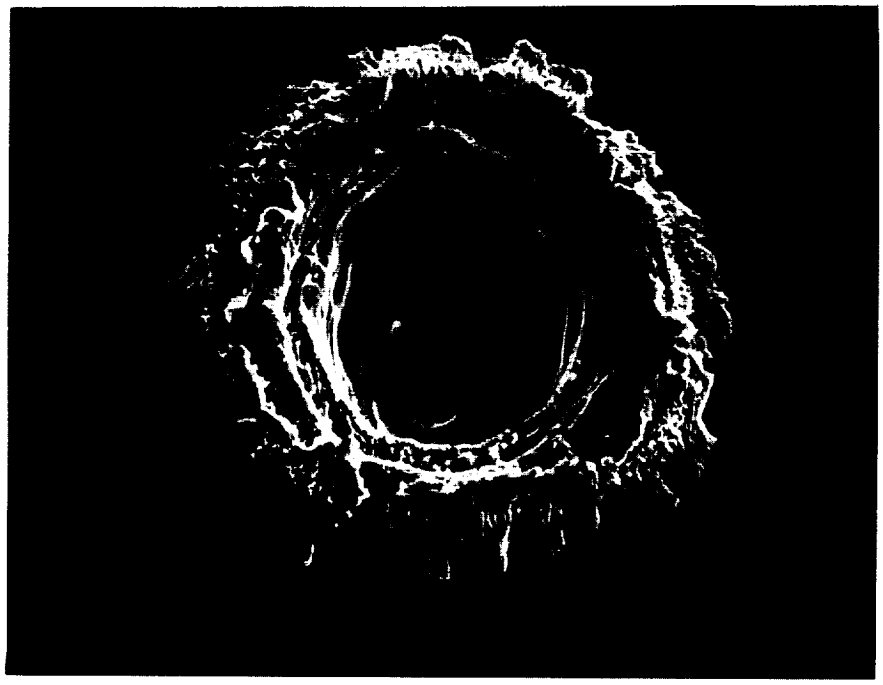
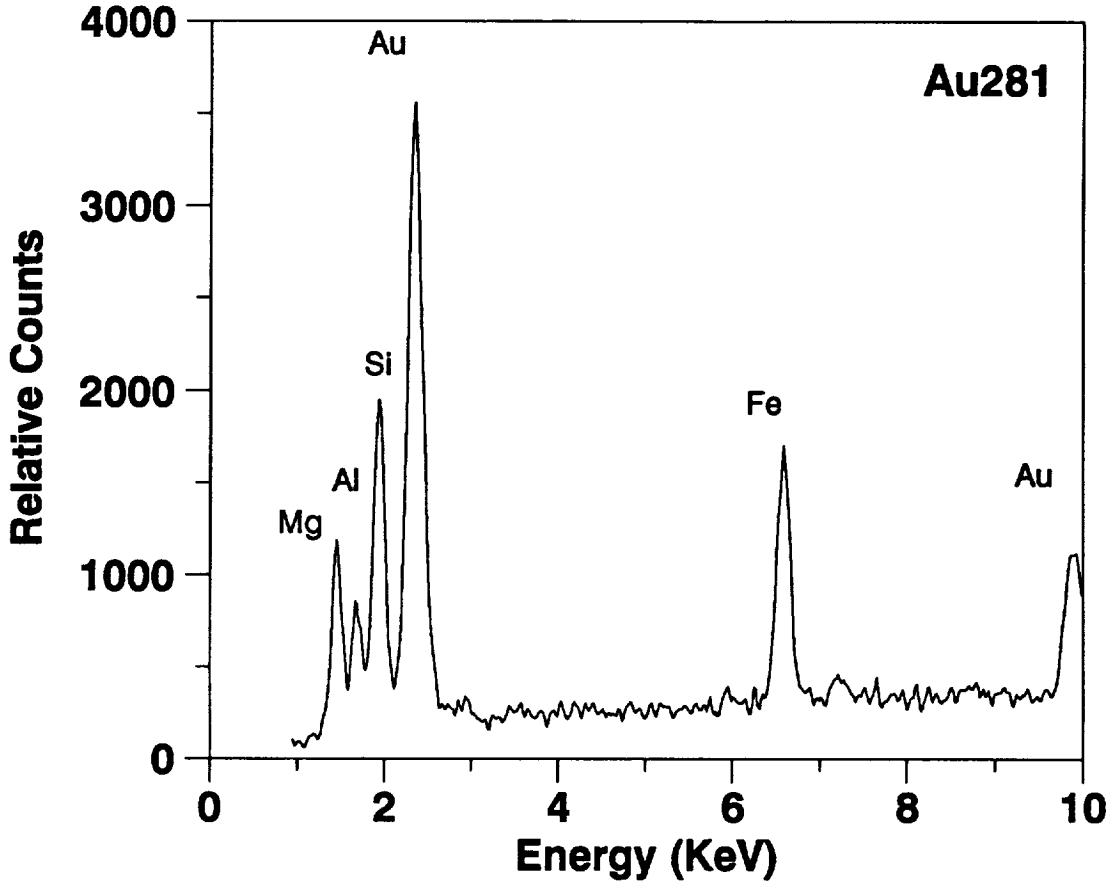


COMPONENT: EOOK
FEATURE: 281
CORE: LD-235

DIAMETER: 40 μm
ORIGIN: Natural



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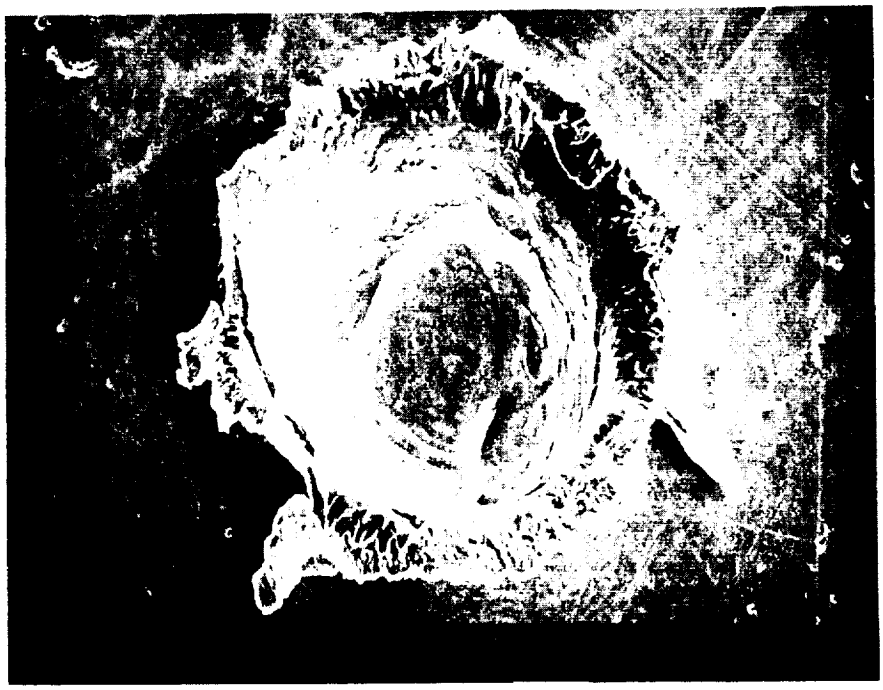
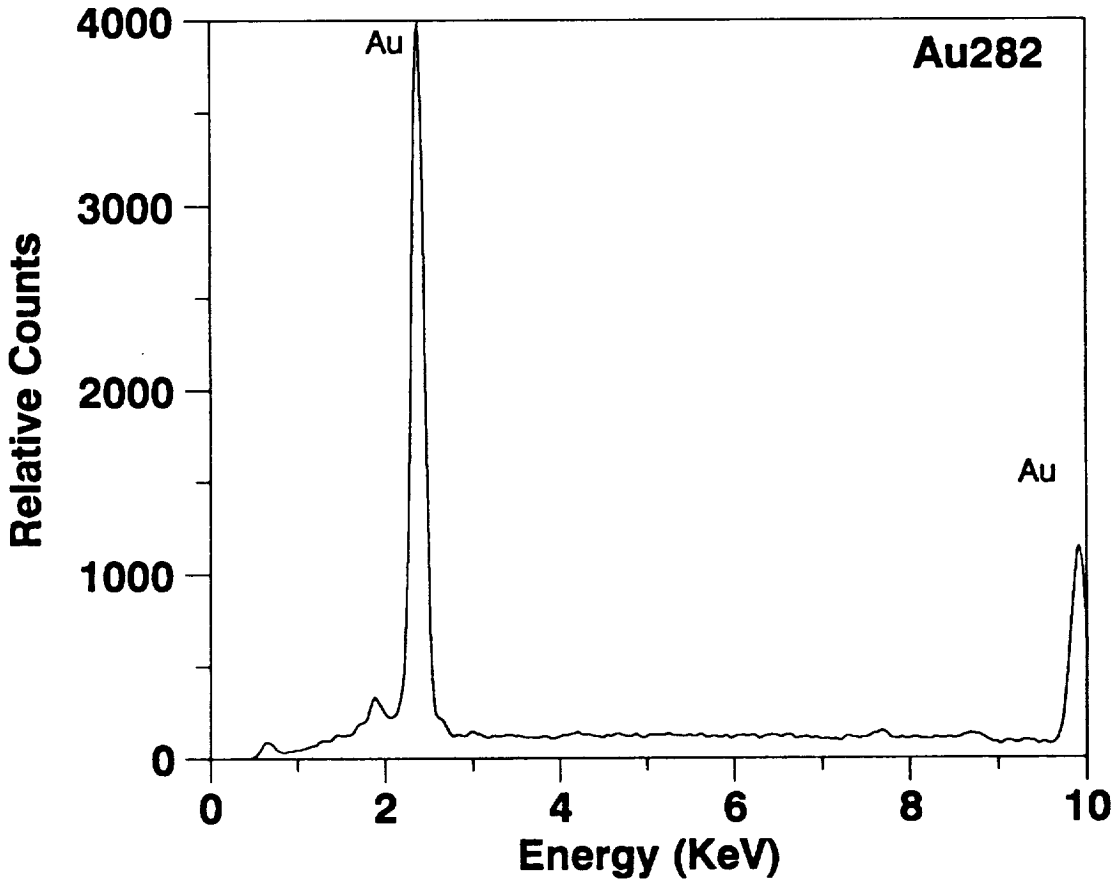


COMPONENT: EOOK
FEATURE: 282
CORE: LD-236

DIAMETER: 75 μm
ORIGIN: Unknown



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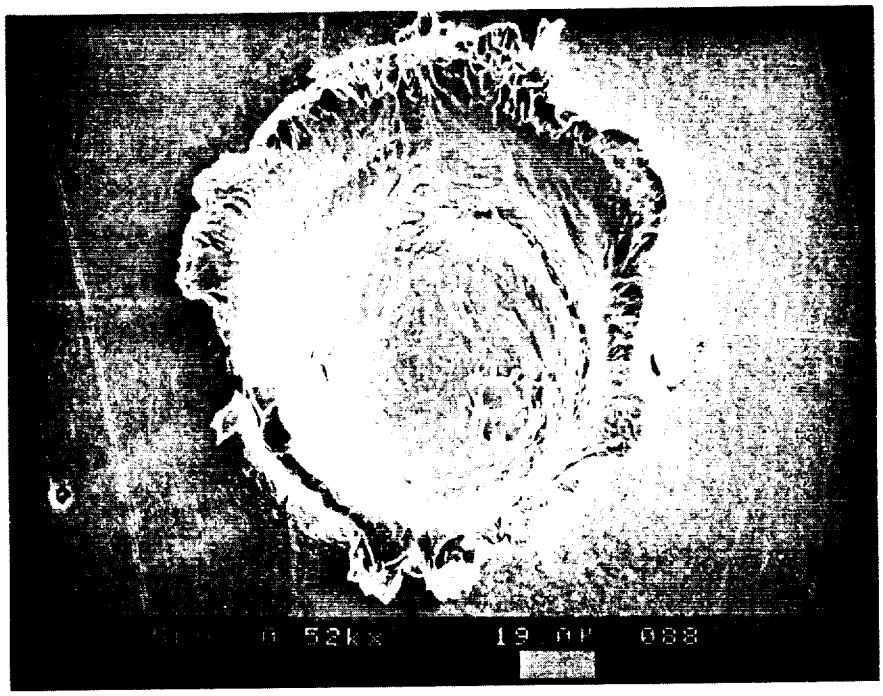
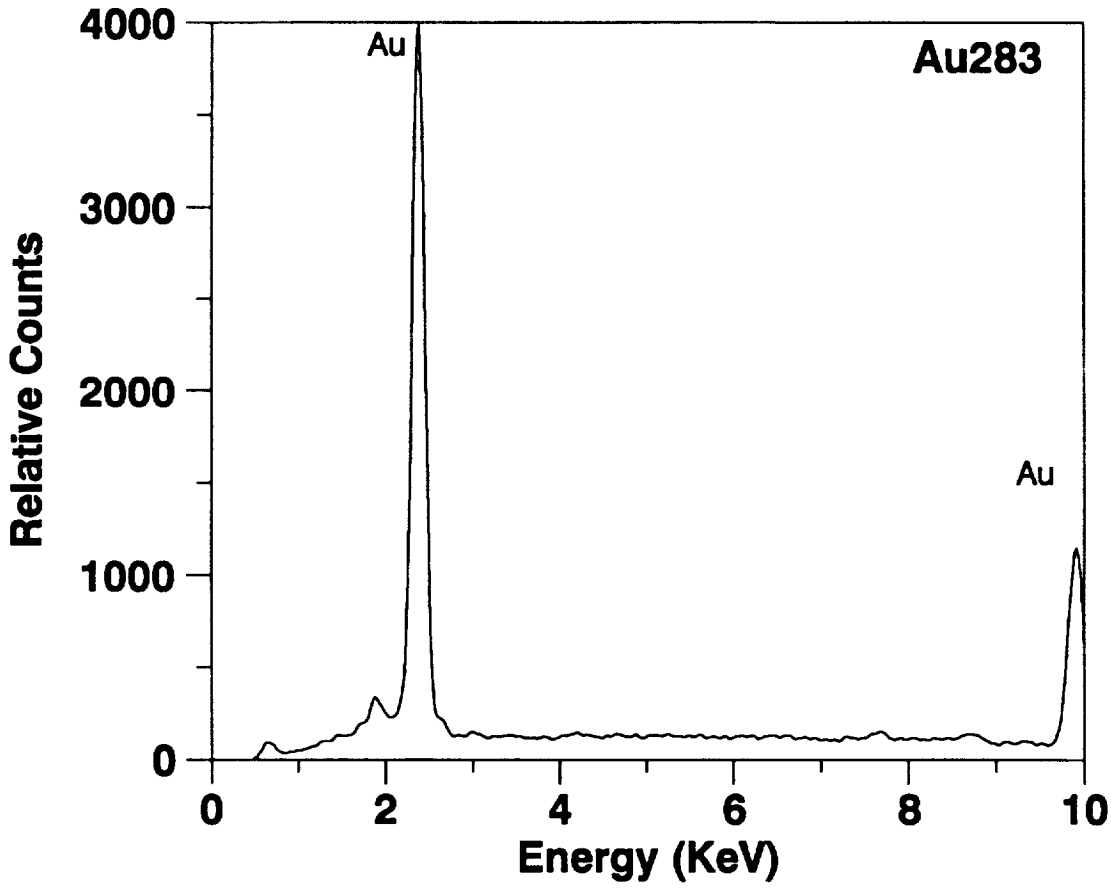


COMPONENT: EOOK
FEATURE: 283
CORE: LD-237

DIAMETER: 90 μm
ORIGIN: Unknown



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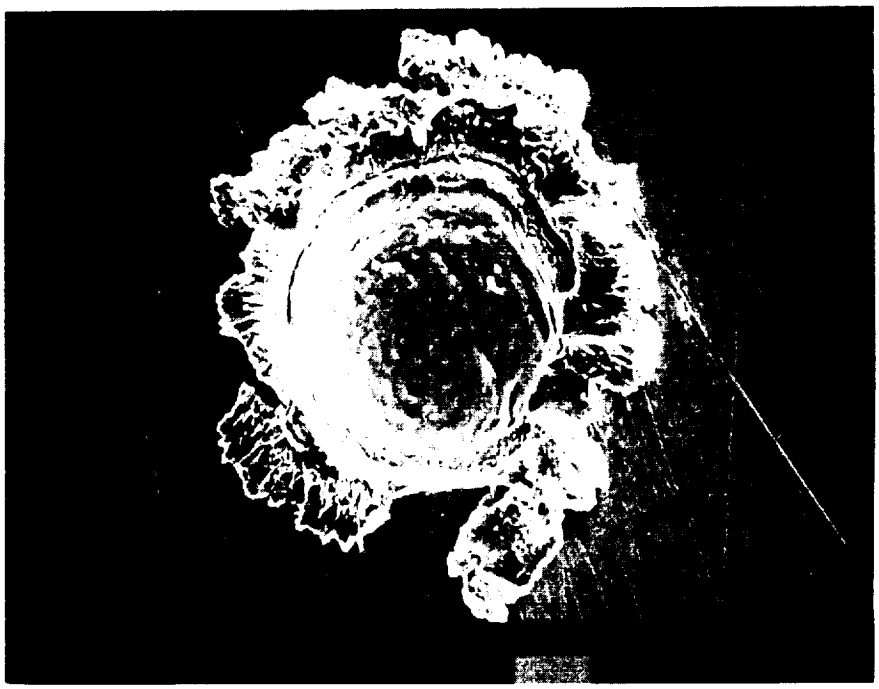
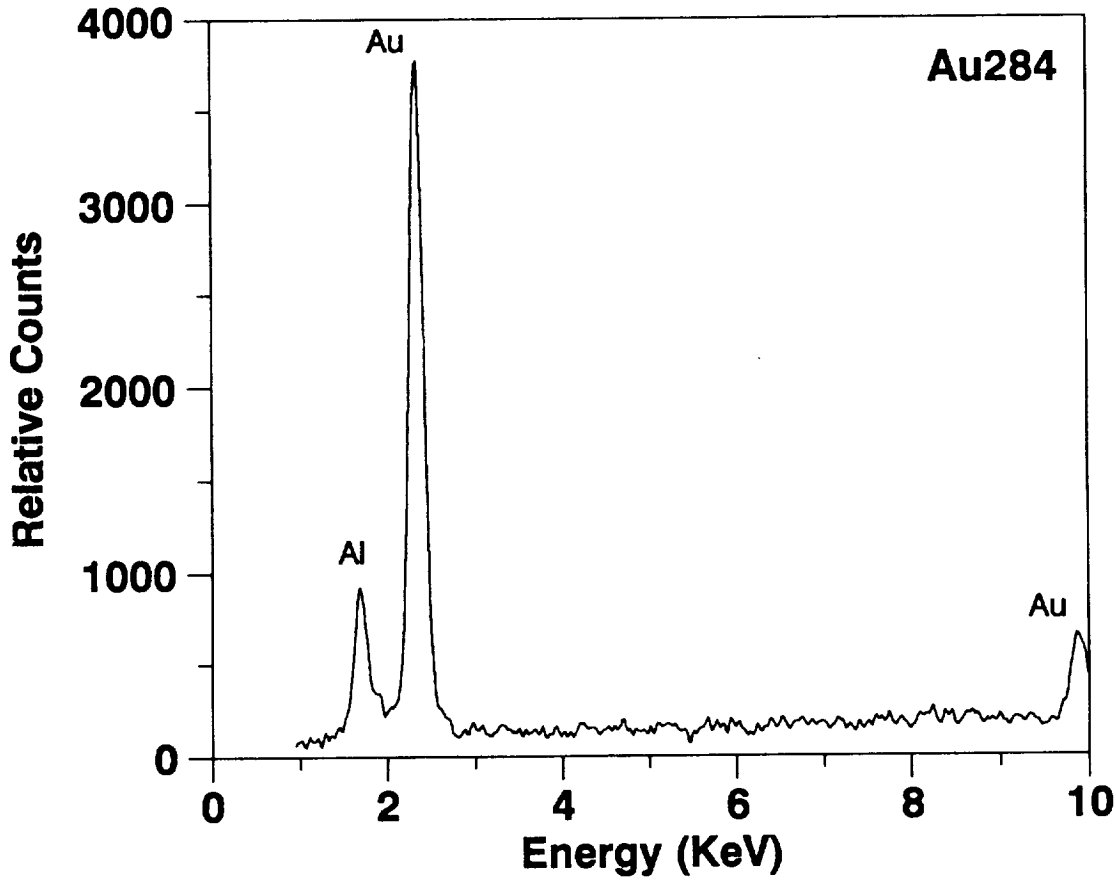


COMPONENT: EOOK
FEATURE: 284
CORE: LD-238

DIAMETER: 45 μm
ORIGIN: Man-made



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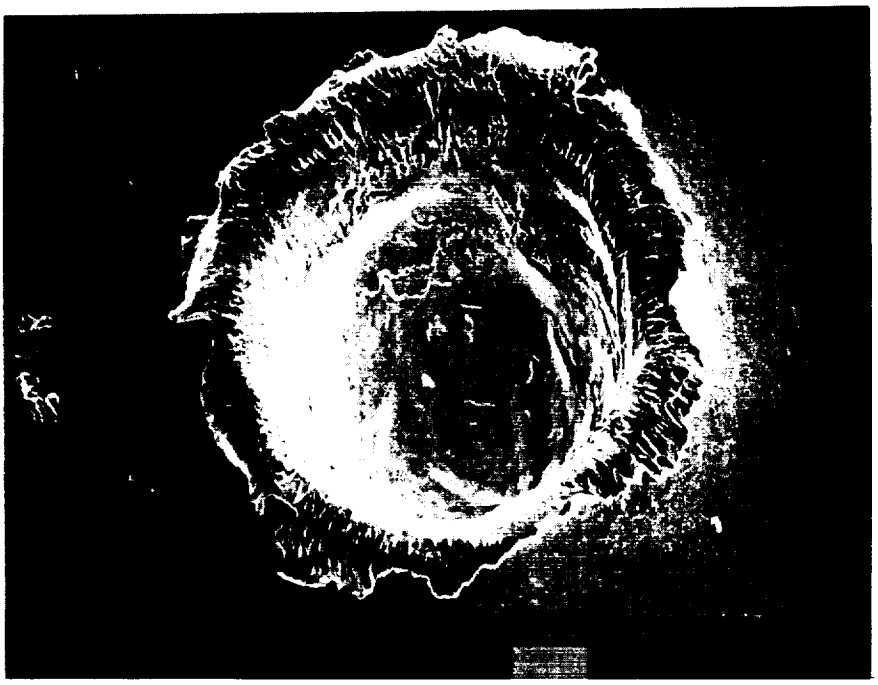
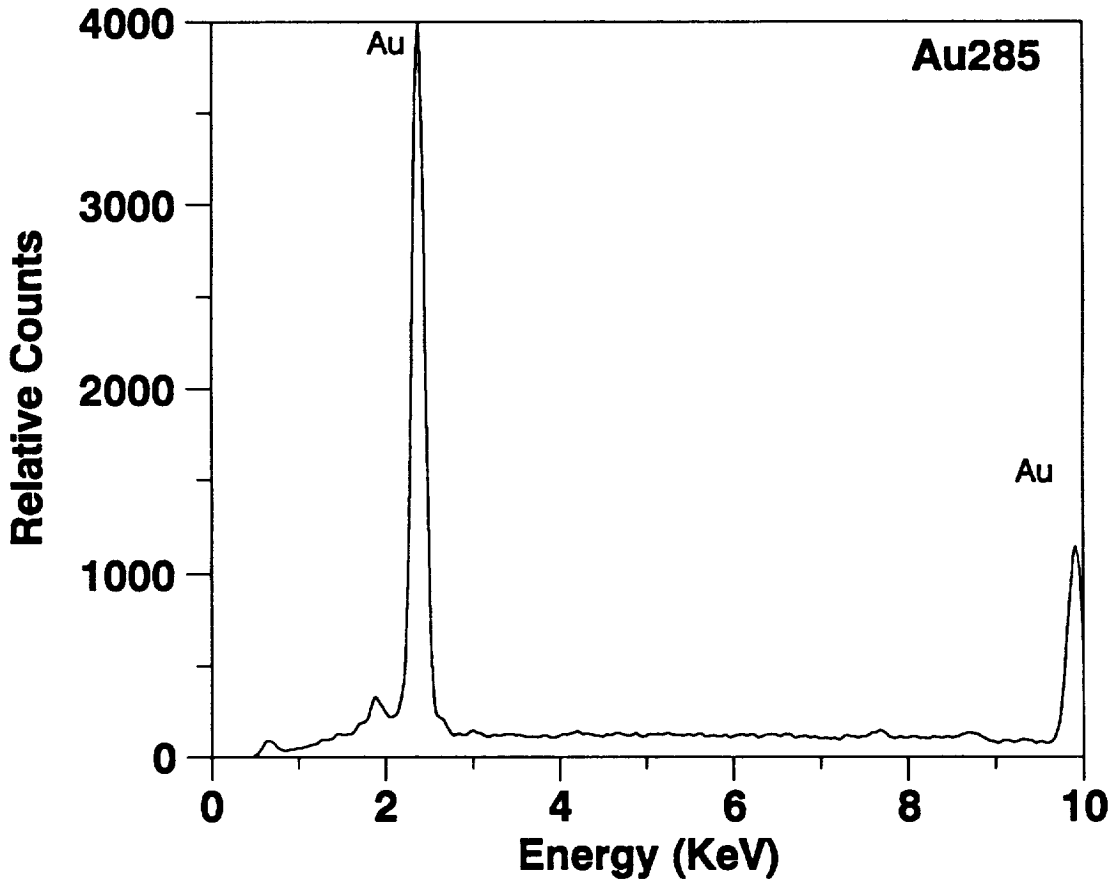


COMPONENT: EOOK
FEATURE: 285
CORE: LD-239

DIAMETER: 195 μm
ORIGIN: Unknown



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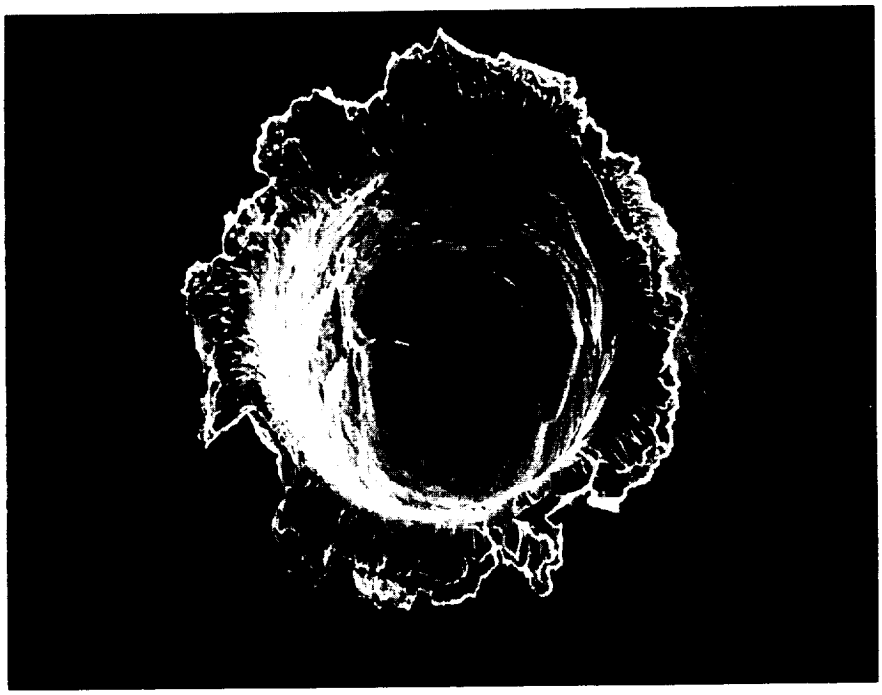
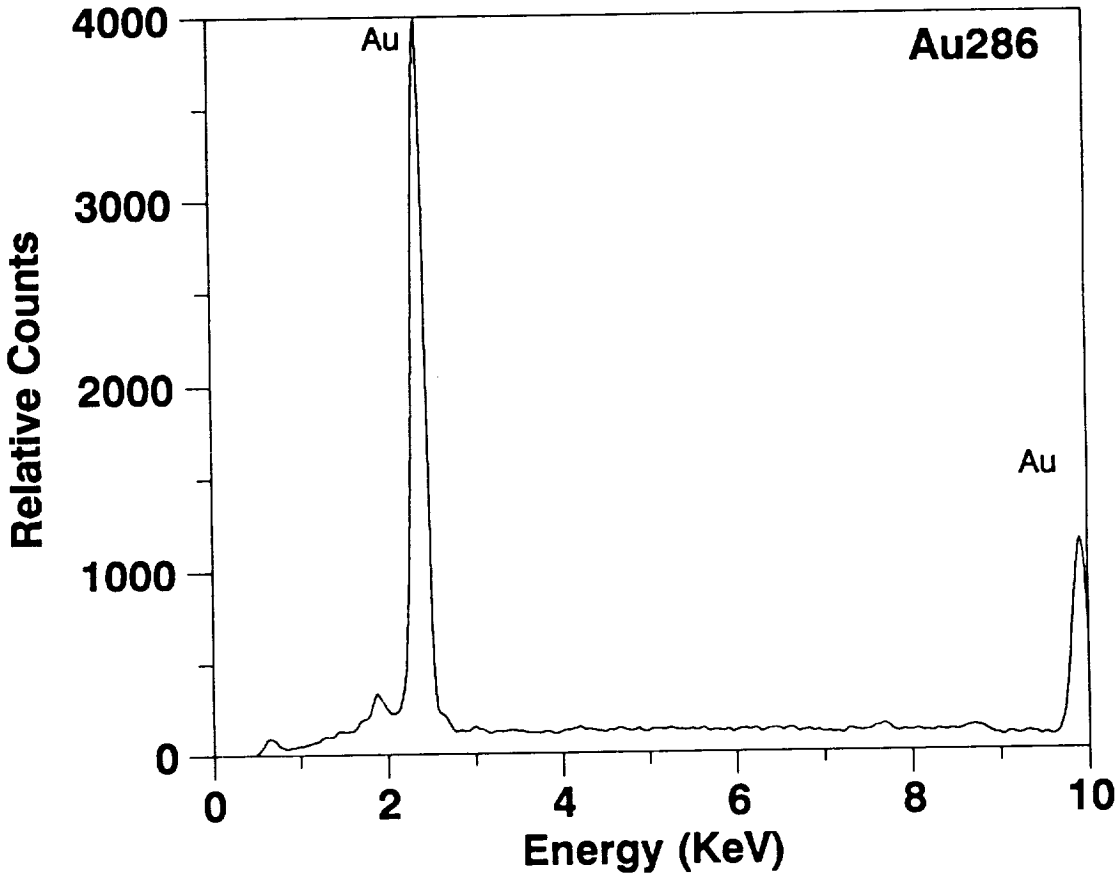


COMPONENT: EOOK
FEATURE: 286
CORE: LD-240

DIAMETER: 85 μm
ORIGIN: Unknown



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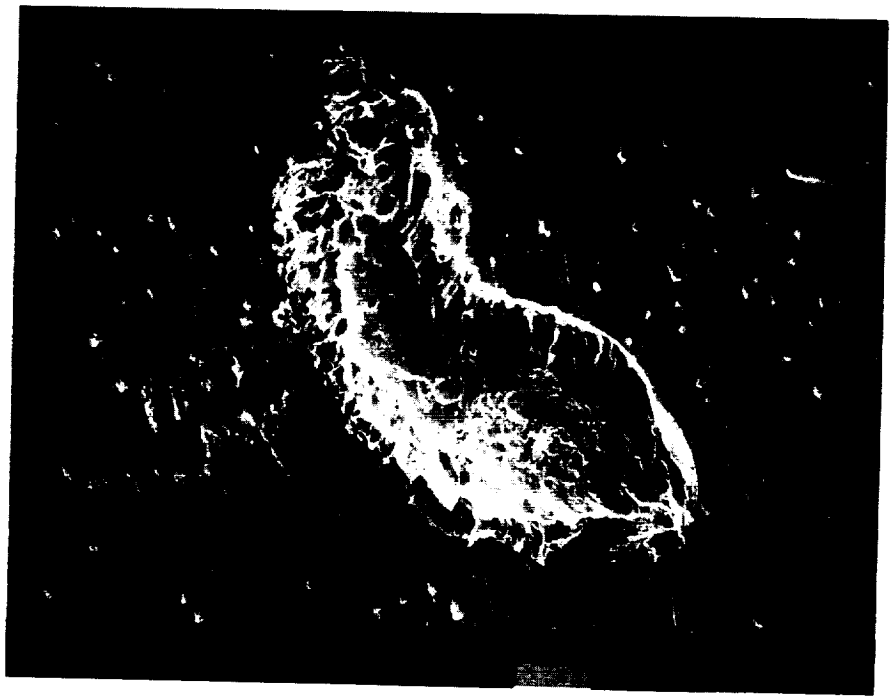
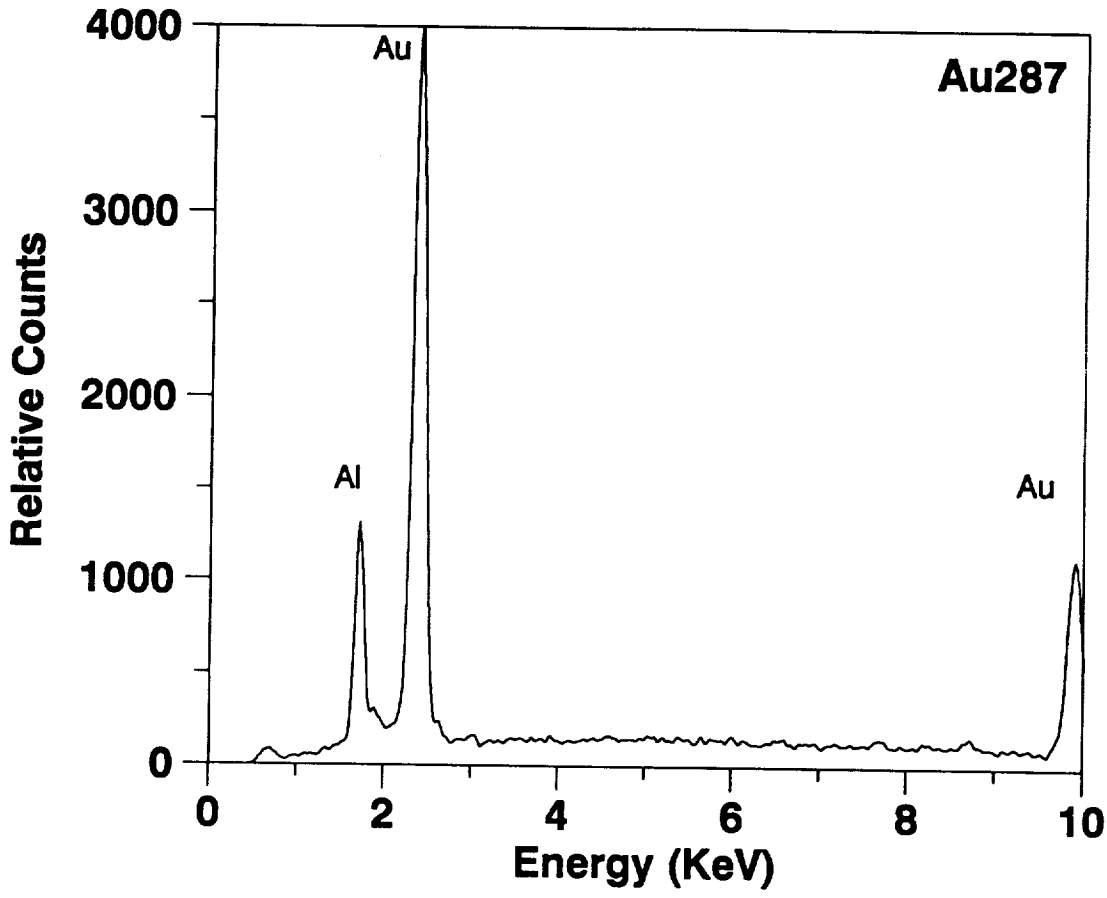


COMPONENT: EOOK
FEATURE: 287
CORE: LD-241

DIAMETER: 145 μm
ORIGIN: Man-made



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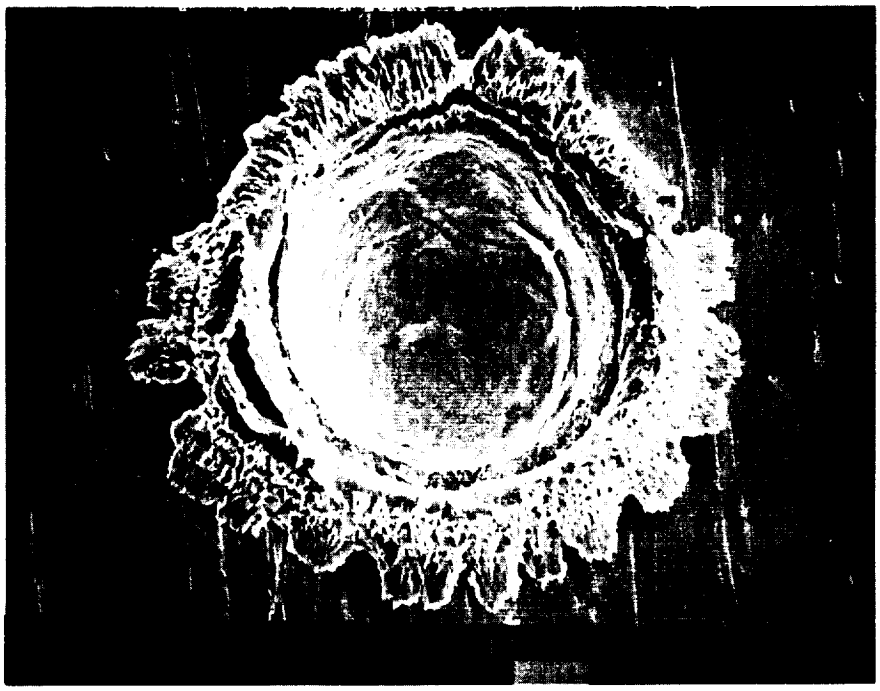
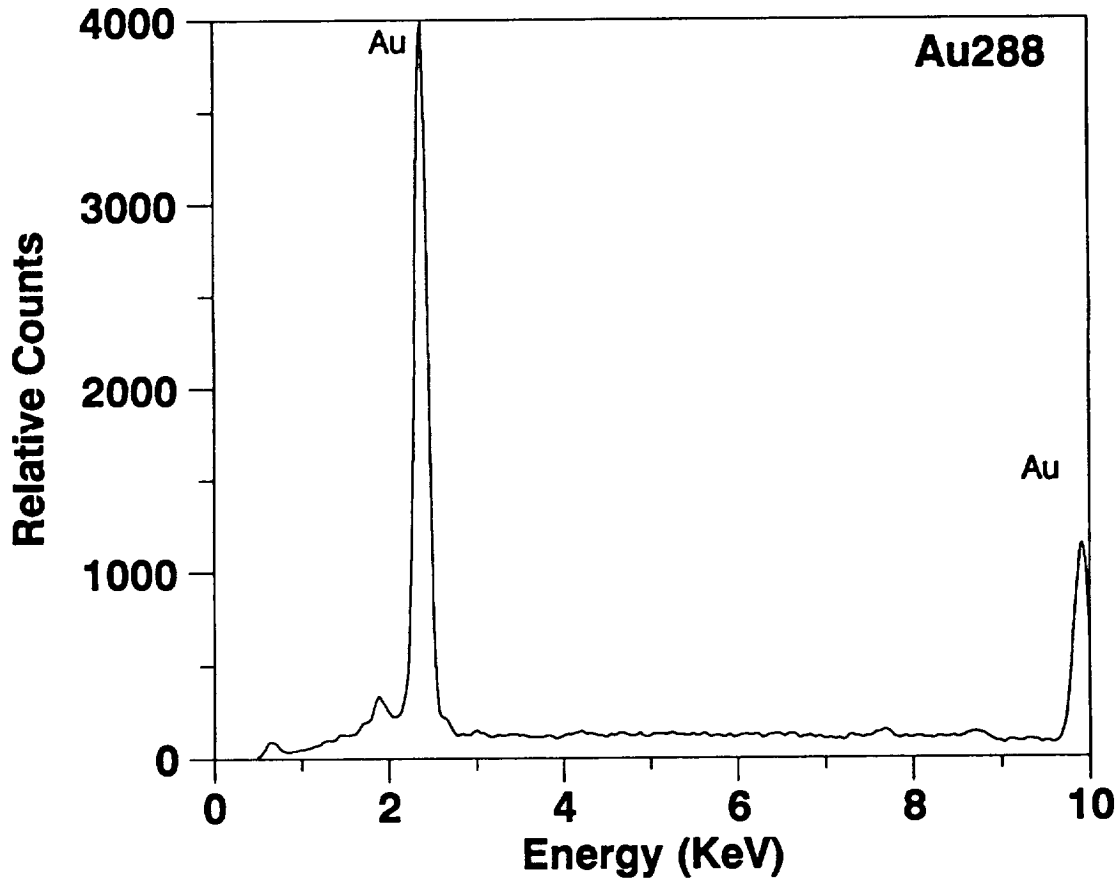


COMPONENT: EOOK
FEATURE: 288
CORE: LD-242

DIAMETER: 55 μm
ORIGIN: Unknown



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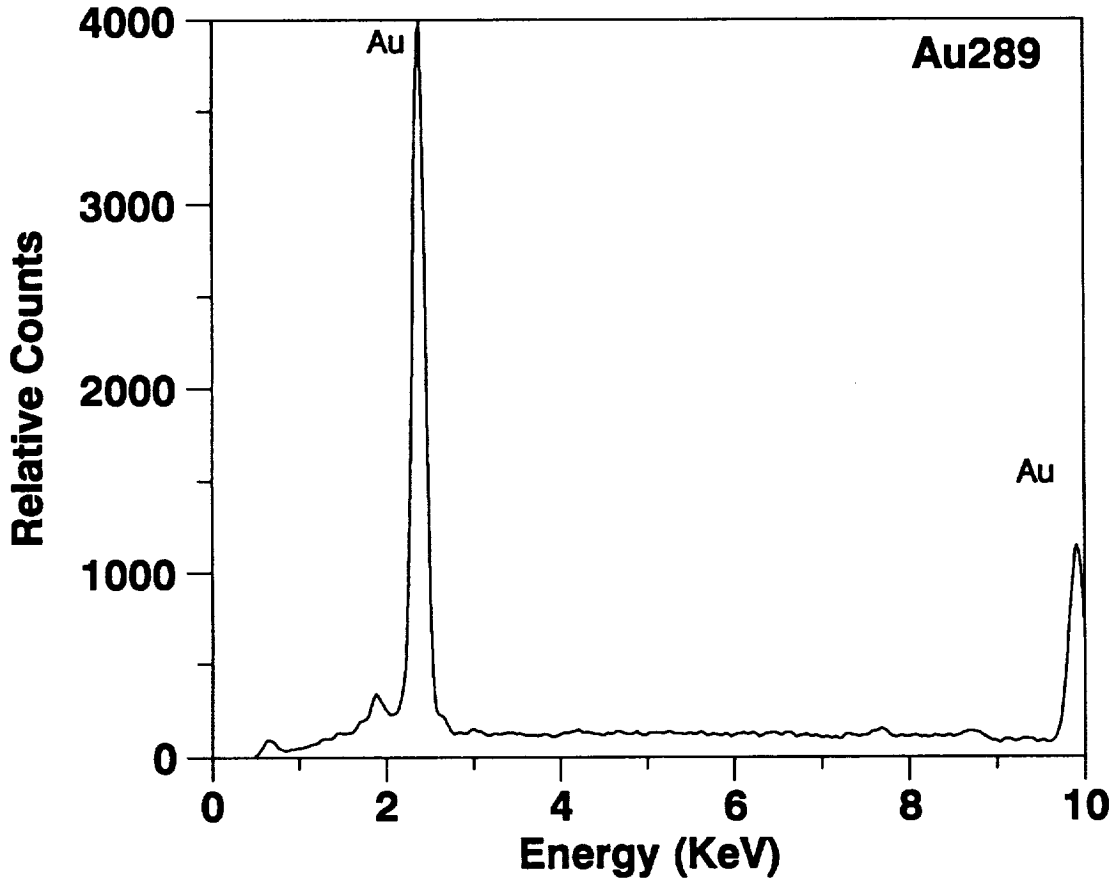
COMPONENT: EOOK
FEATURE: 289
CORE: LD-255

DIAMETER: 260 μm
ORIGIN: Unknown



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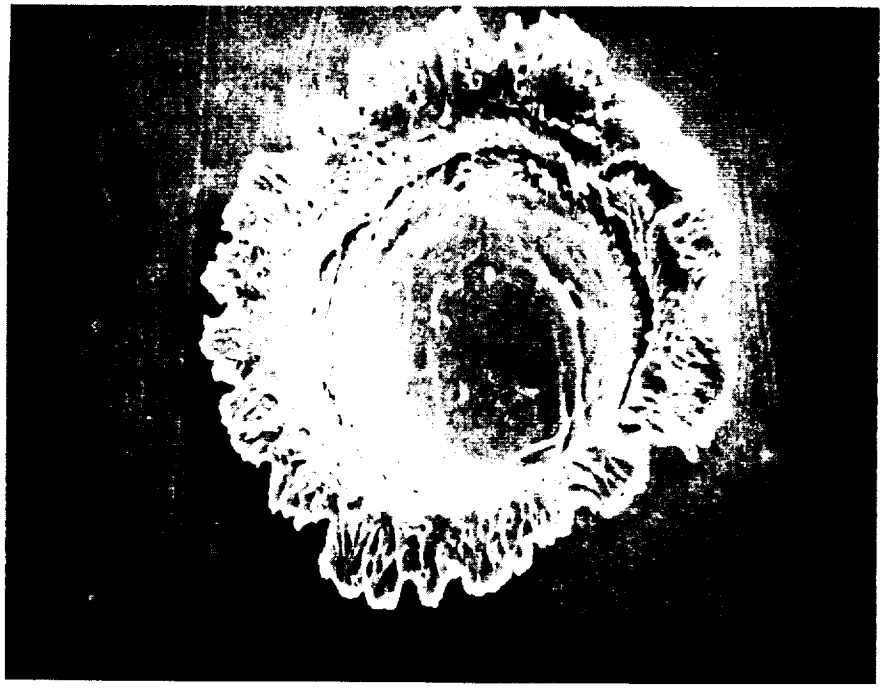
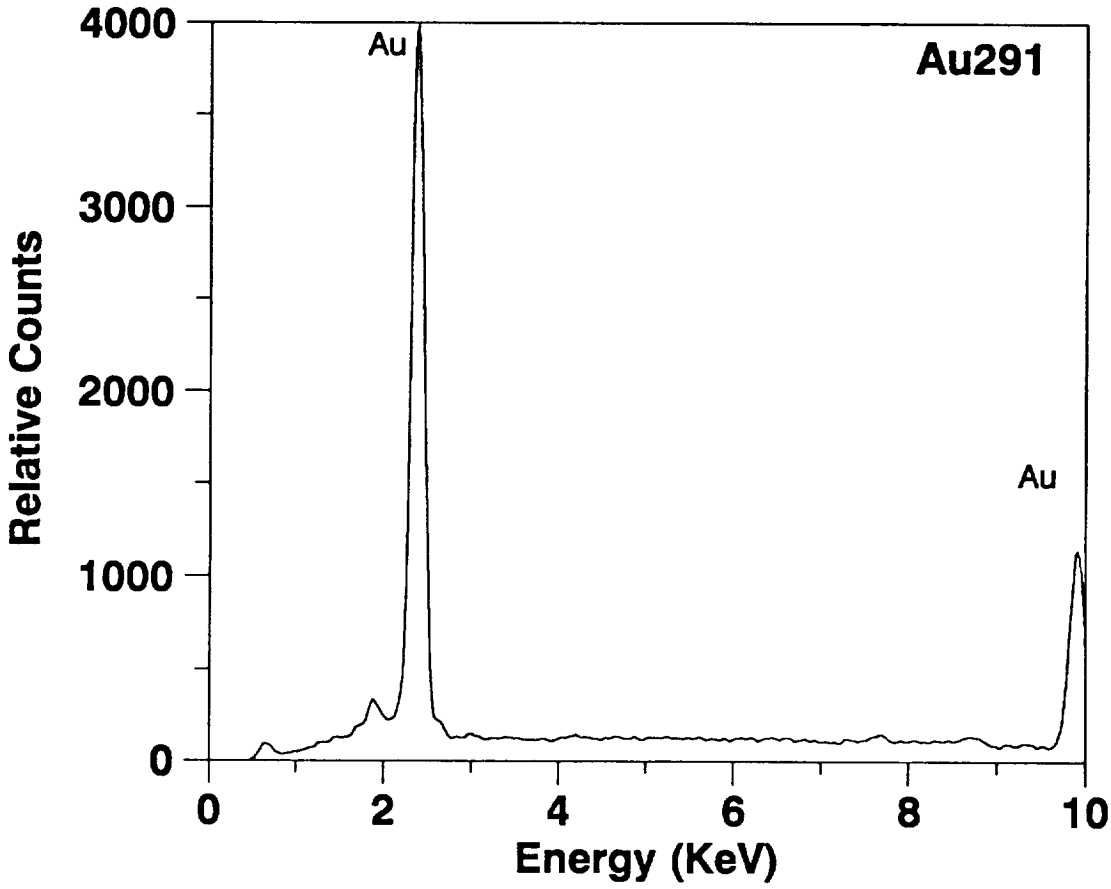


COMPONENT: EOOK
FEATURE: 291
CORE: LD-257

DIAMETER: 35 μm
ORIGIN: Unknown



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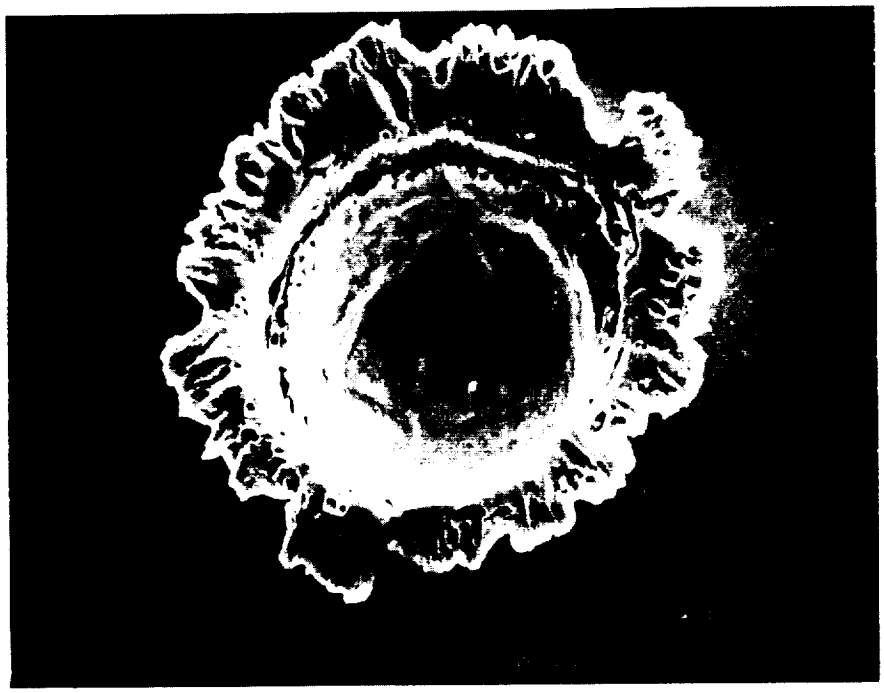
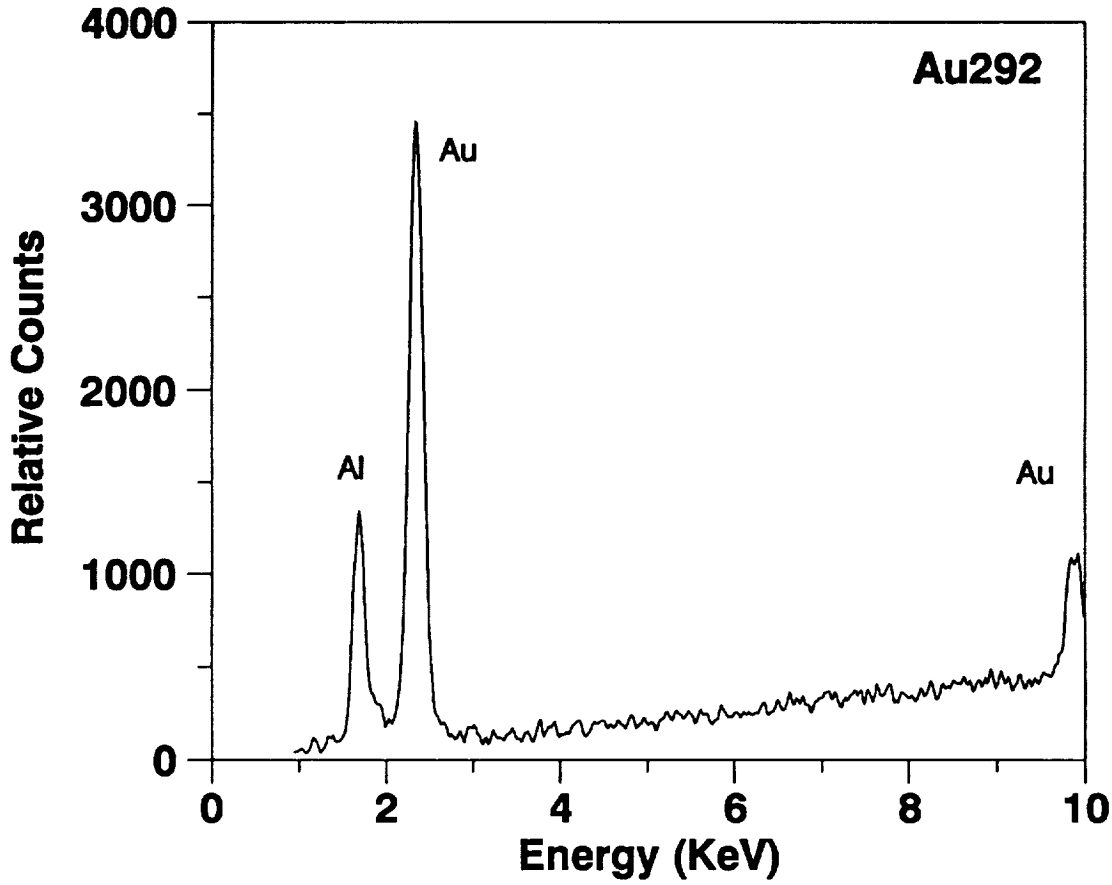


COMPONENT: EOOK
FEATURE: 292
CORE: LD-258

DIAMETER: 15 μm
ORIGIN: Man-made



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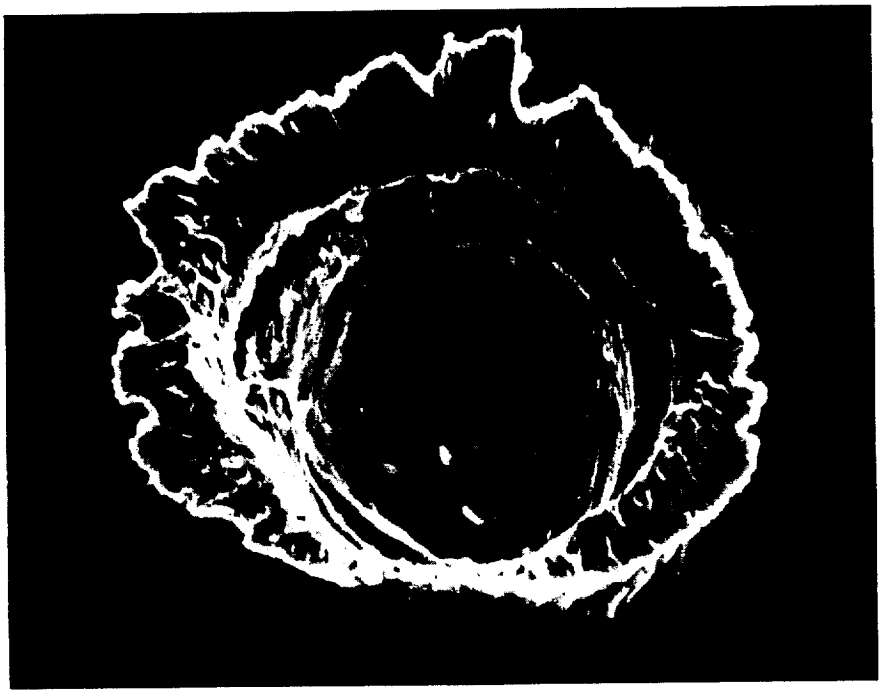
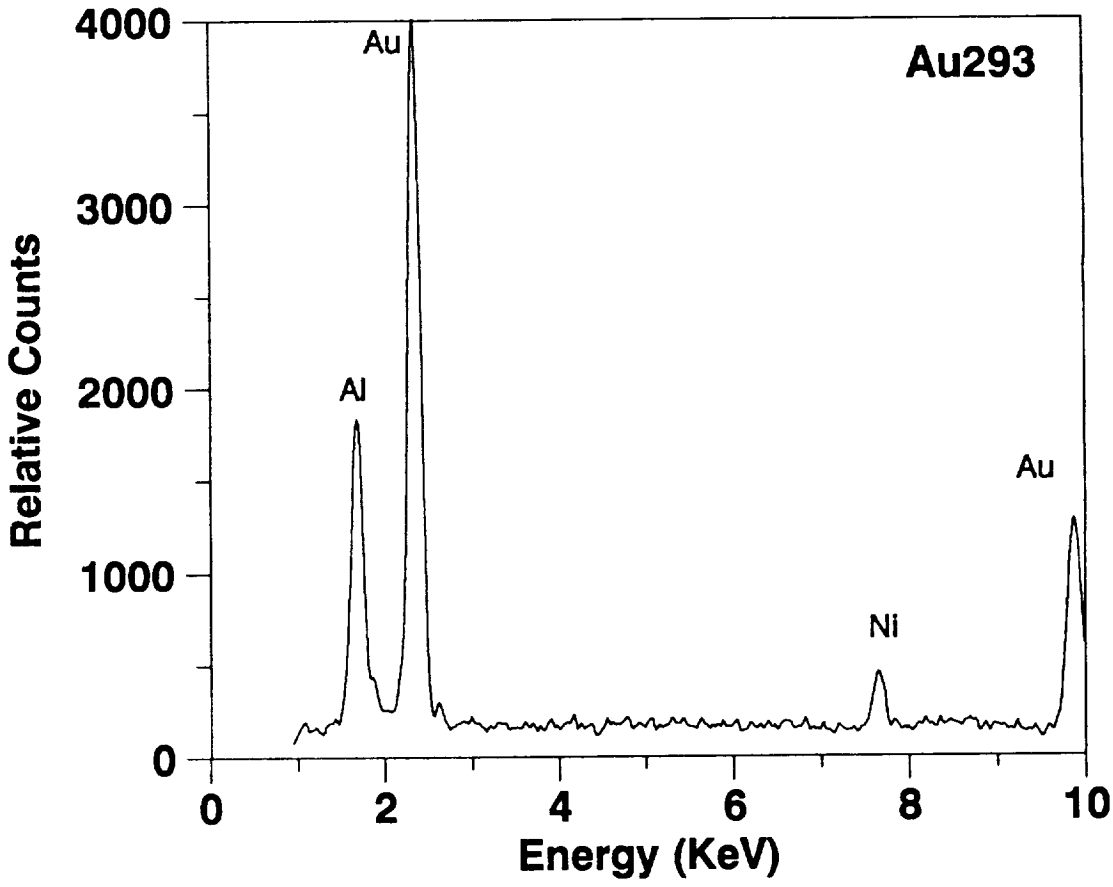


COMPONENT: EOOK
FEATURE: 293
CORE: LD-243

DIAMETER: 15 μm
ORIGIN: Man-made



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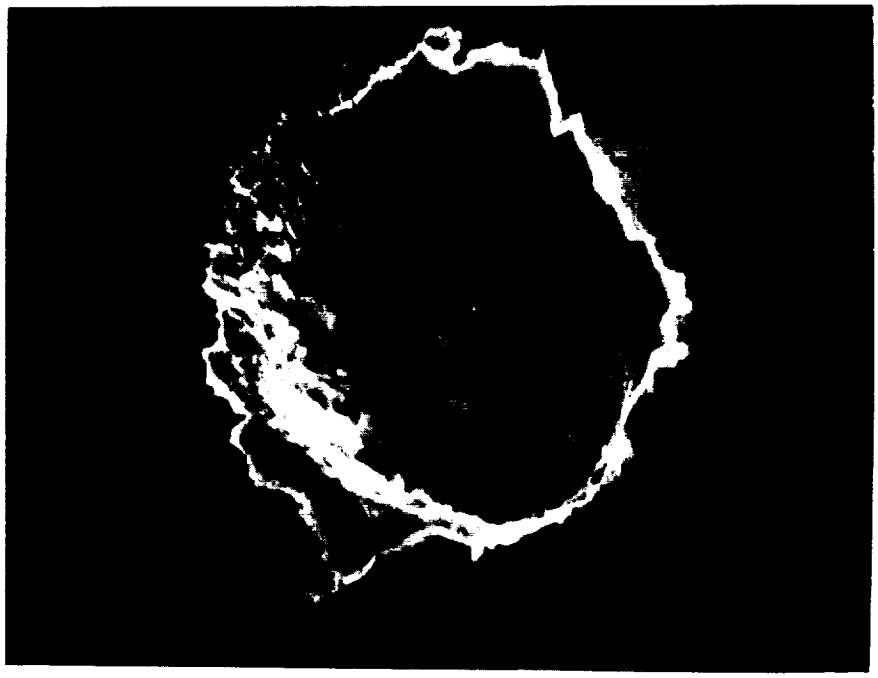
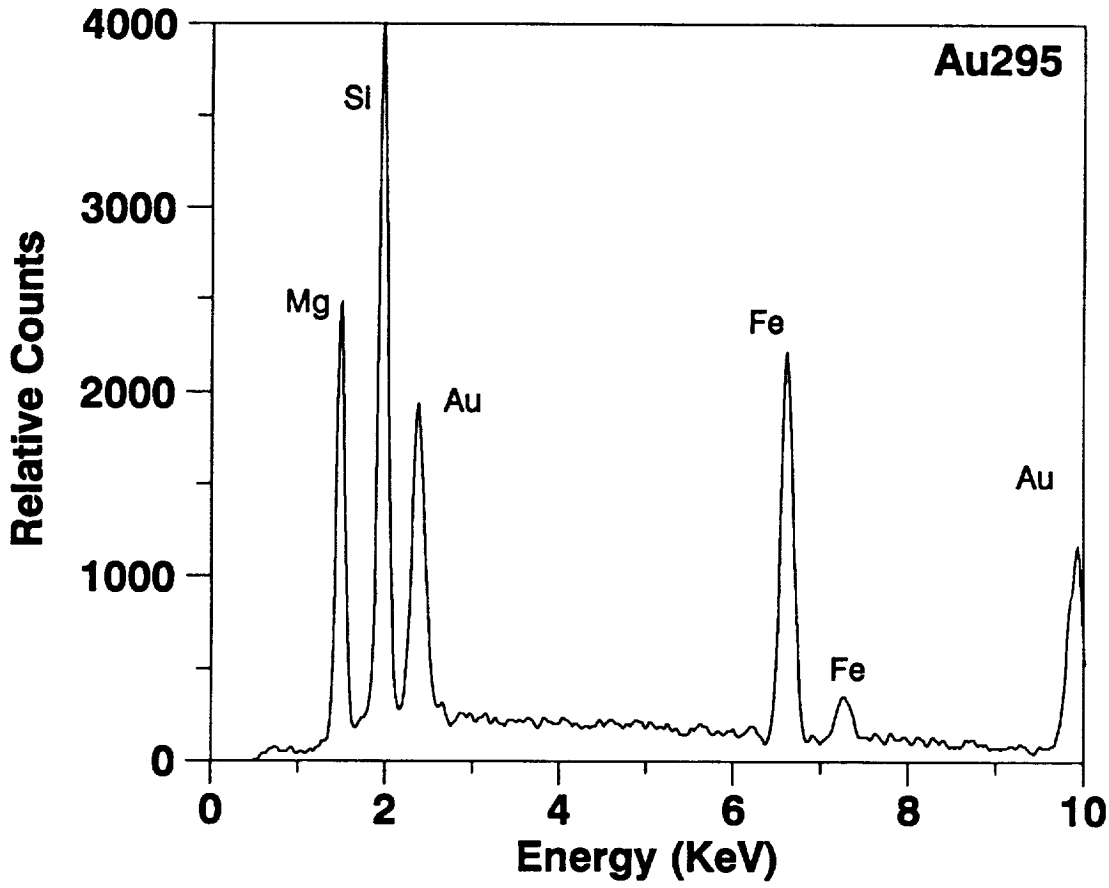


COMPONENT: EOOK
FEATURE: 295
CORE: LD-245

DIAMETER: 15 μm
ORIGIN: Natural



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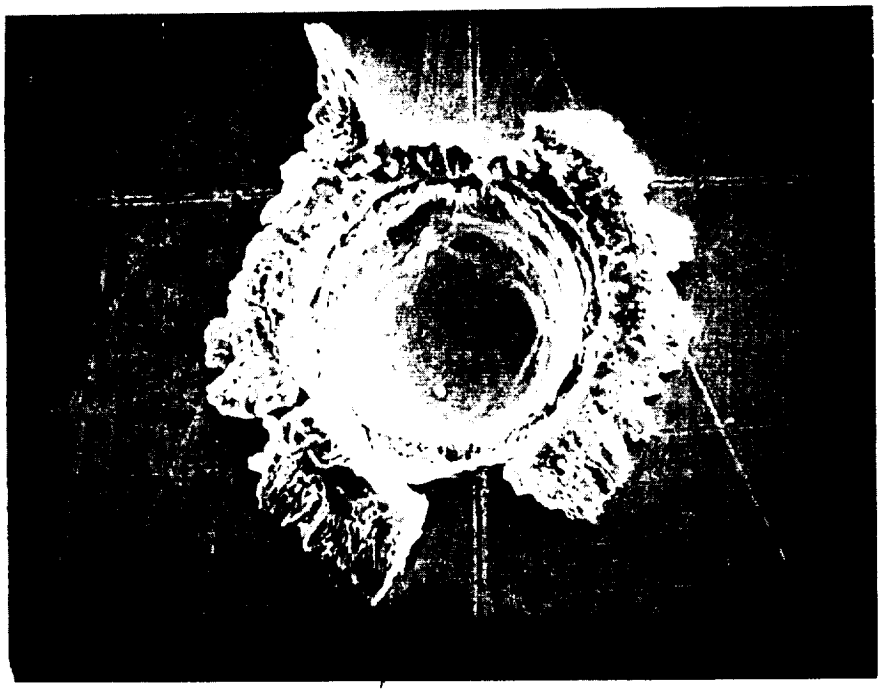
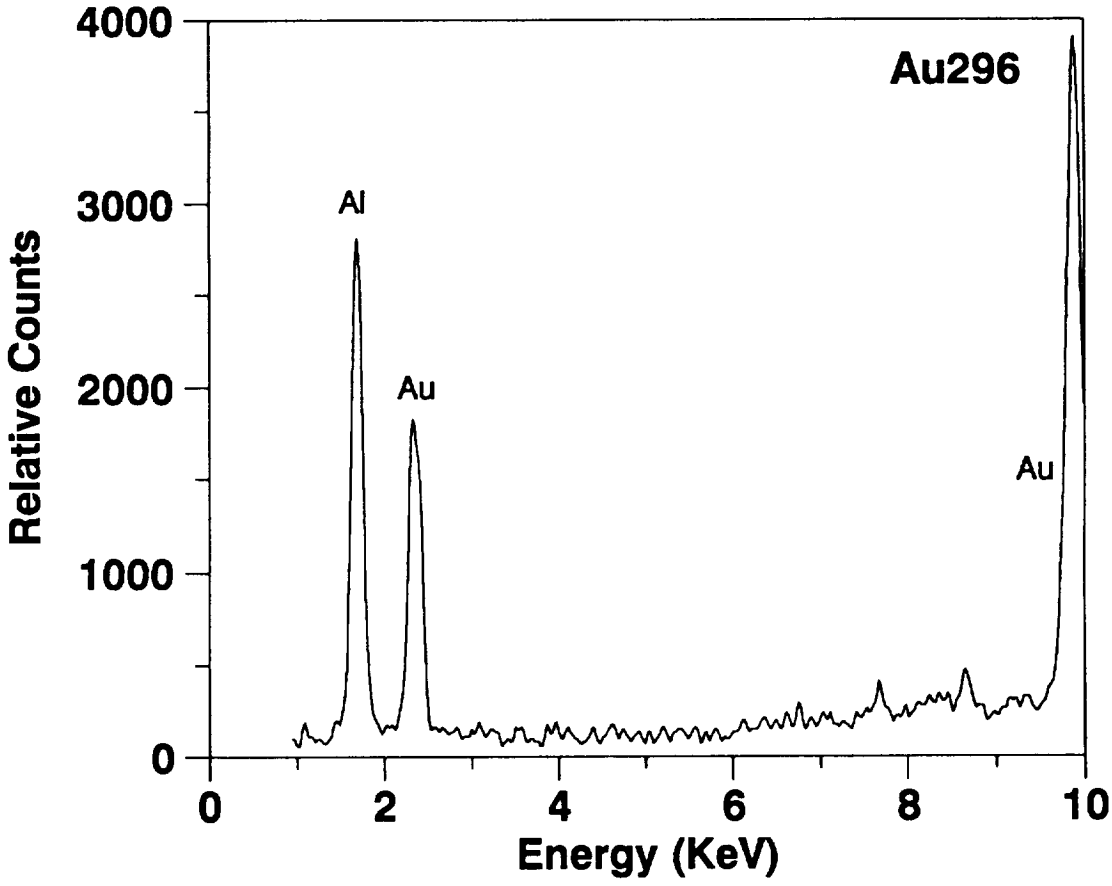


COMPONENT: EOOK
FEATURE: 296
CORE: LD-246

DIAMETER: 20 μm
ORIGIN: Man-made



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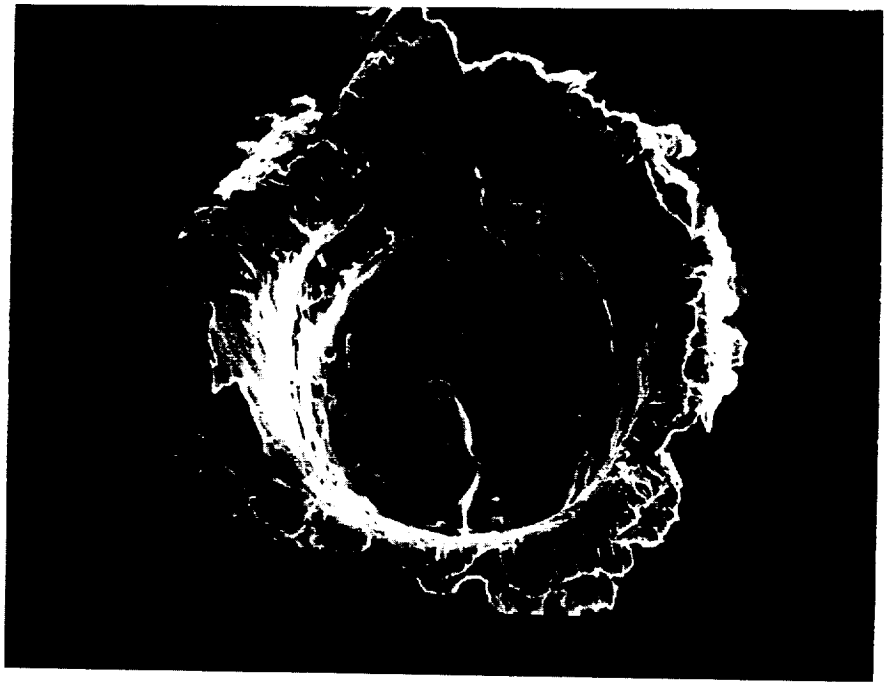
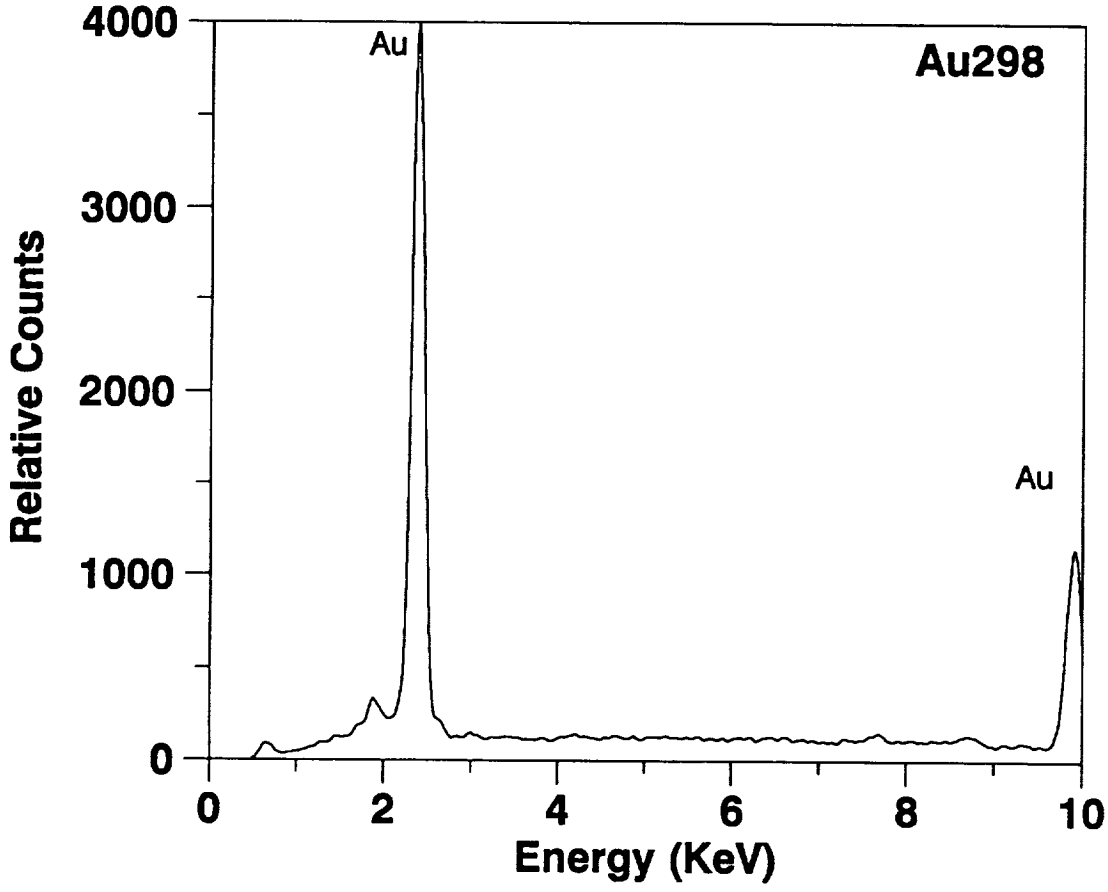


COMPONENT: EOOK
FEATURE: 298
CORE: LD-248

DIAMETER: 85 μm
ORIGIN: Unknown



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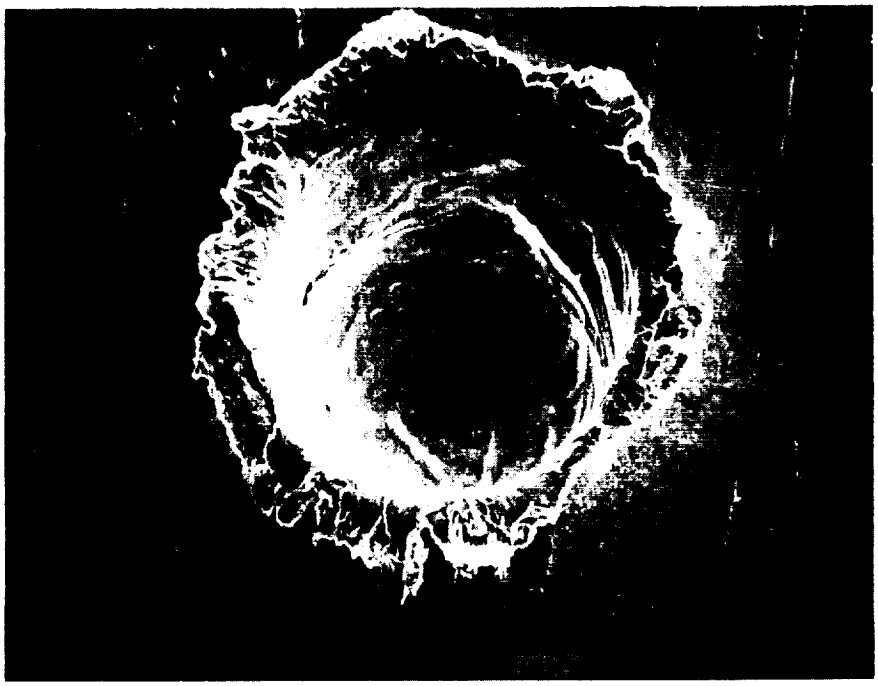
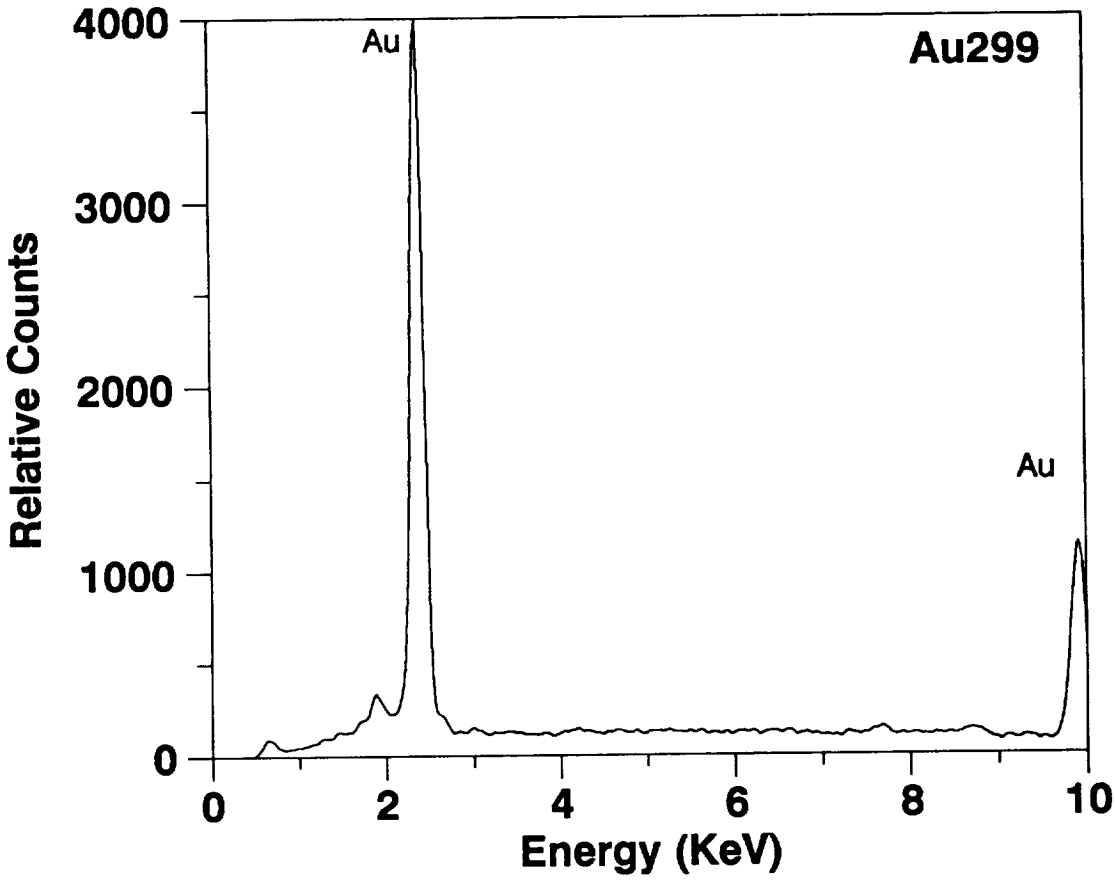


COMPONENT: EOOK
FEATURE: 299
CORE: LD-249

DIAMETER: 80 μm
ORIGIN: Unknown



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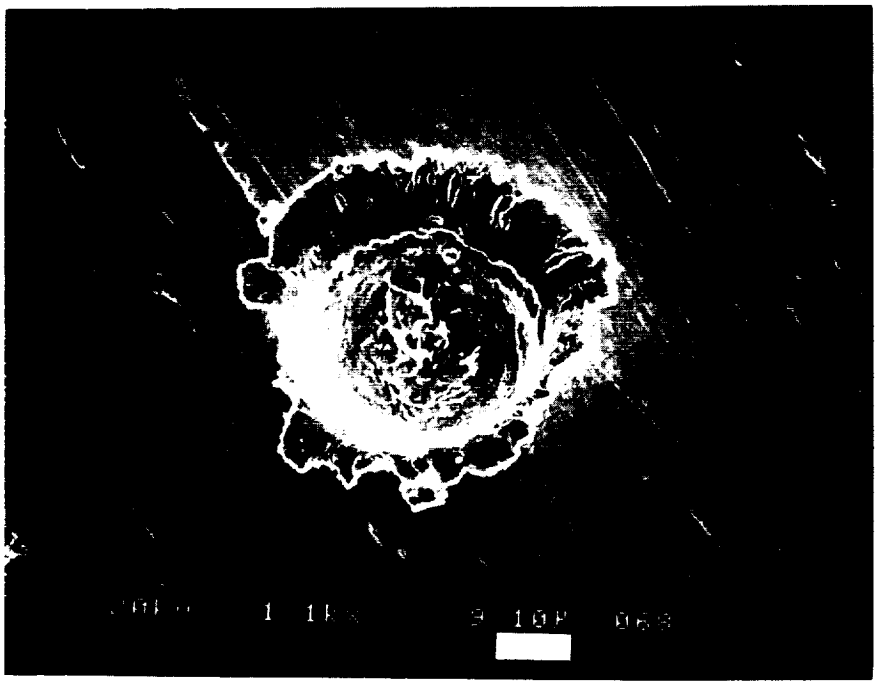
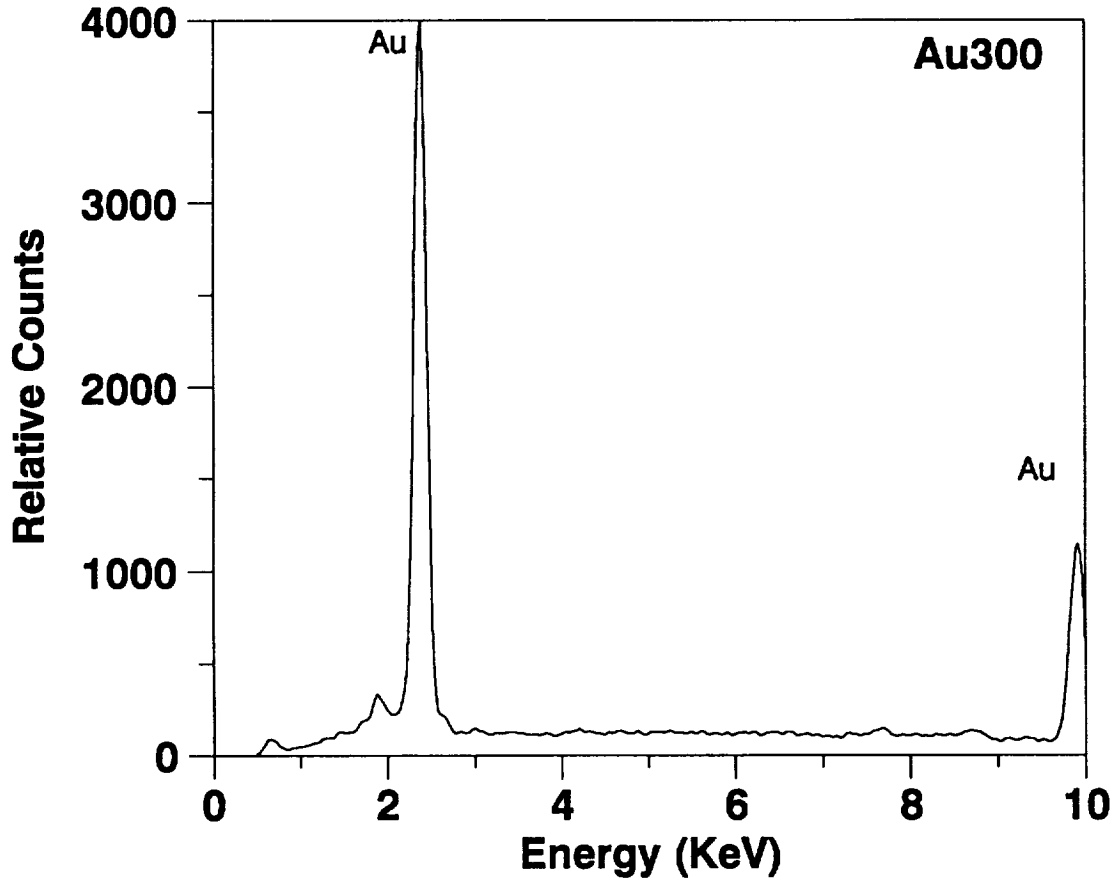


COMPONENT: EOOK
FEATURE: 300
CORE: LD-250

DIAMETER: 35 μm
ORIGIN: Unknown



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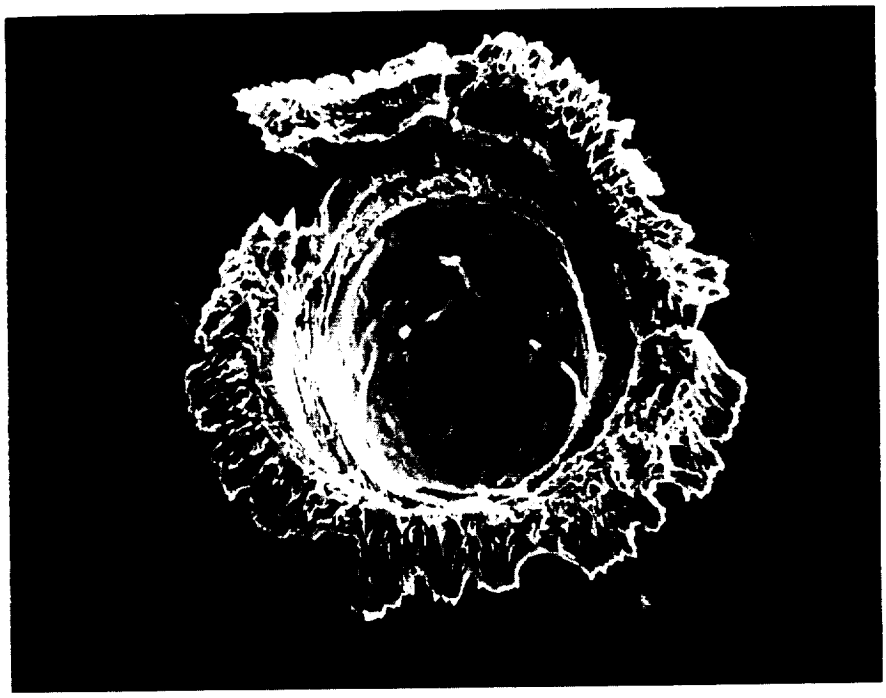
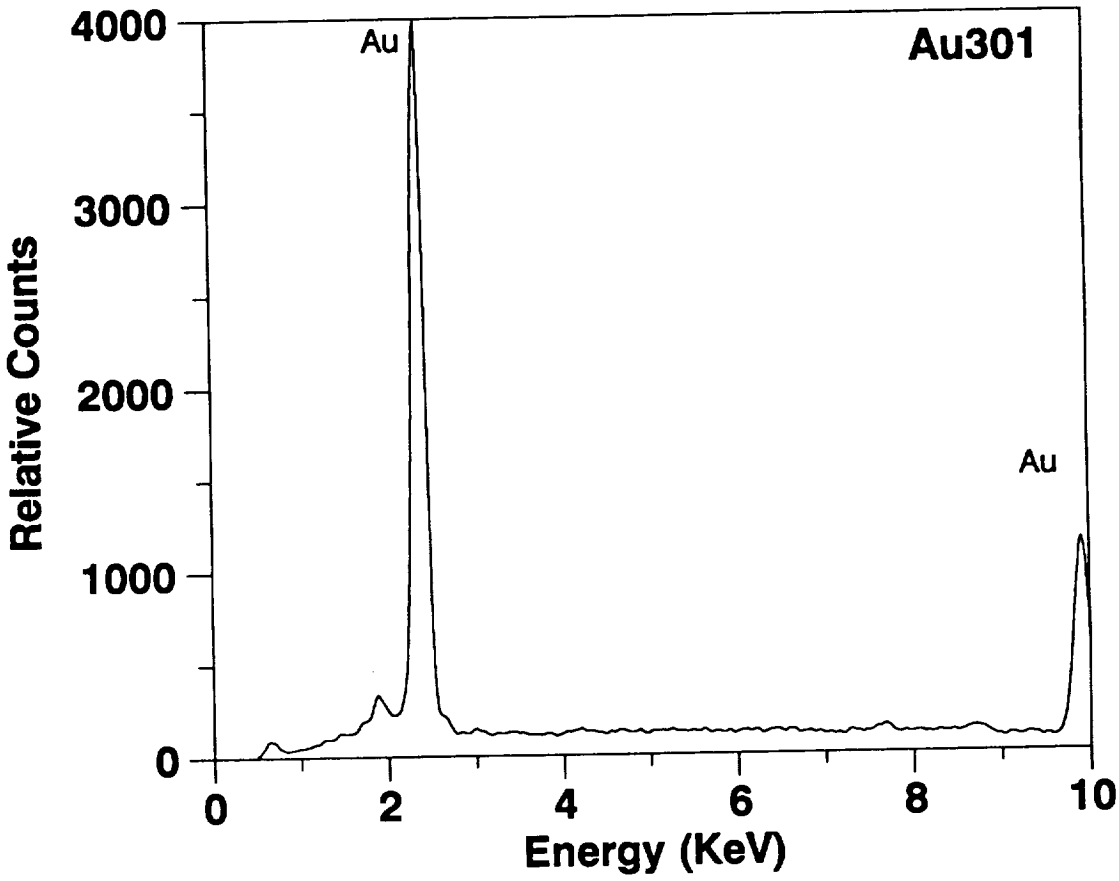


COMPONENT: EOOK
FEATURE: 301
CORE: LD-251

DIAMETER: 45 μm
ORIGIN: Unknown



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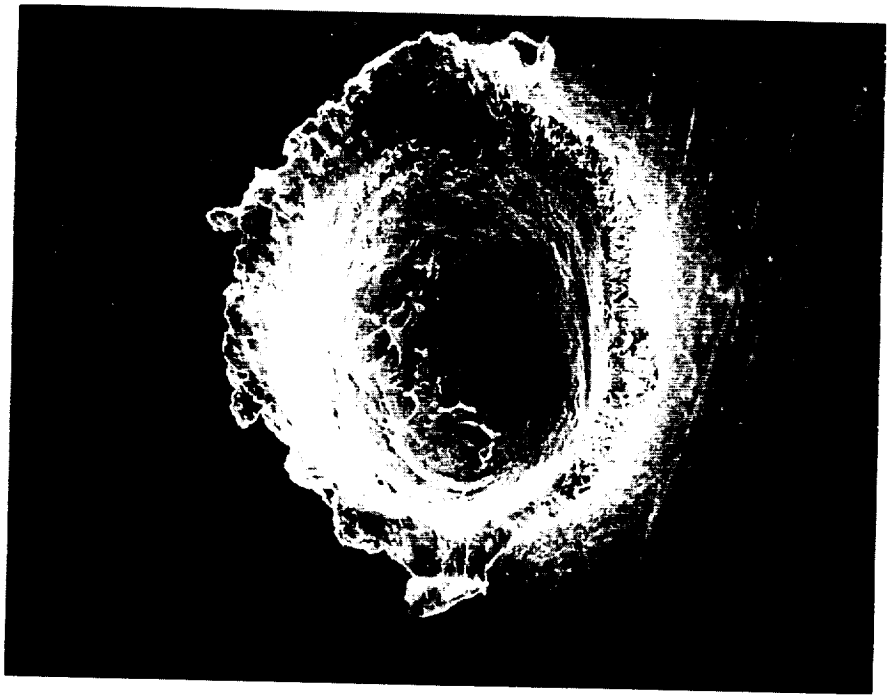
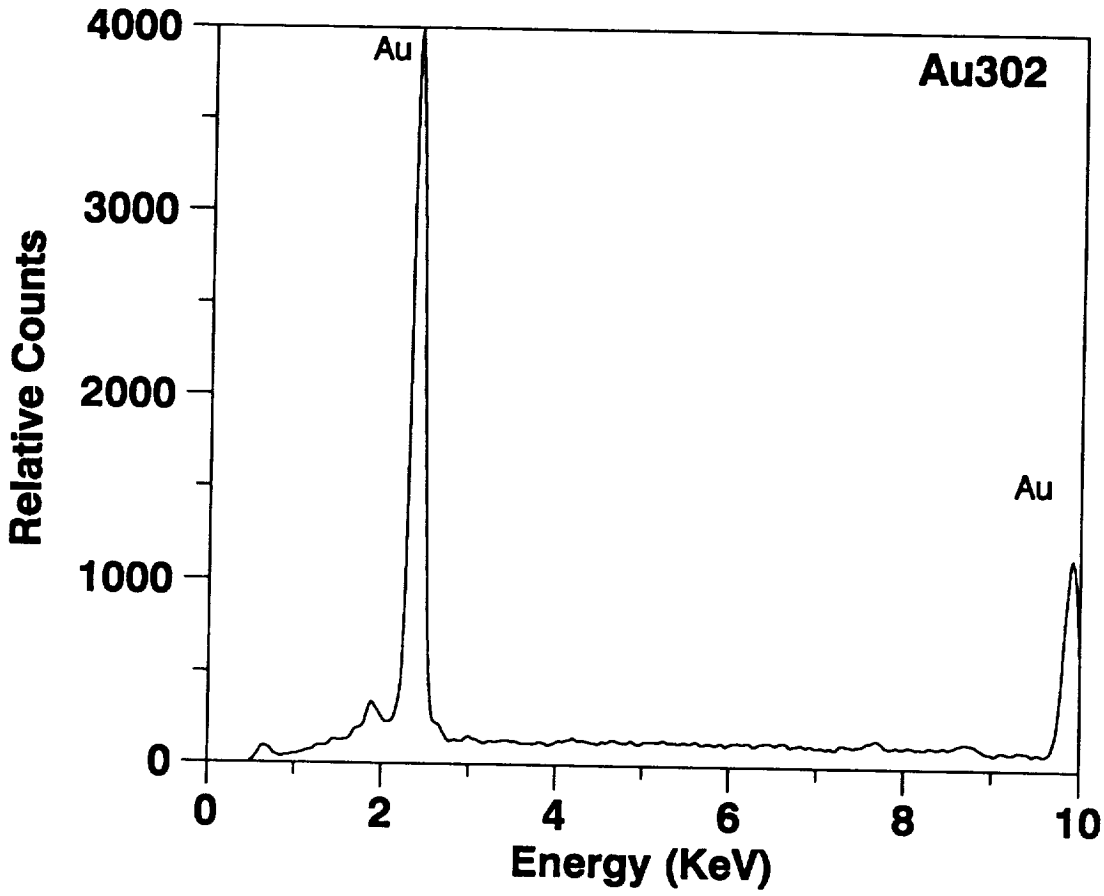


COMPONENT: EOOK
FEATURE: 302
CORE: LD-252

DIAMETER: 125 μm
ORIGIN: Unknown



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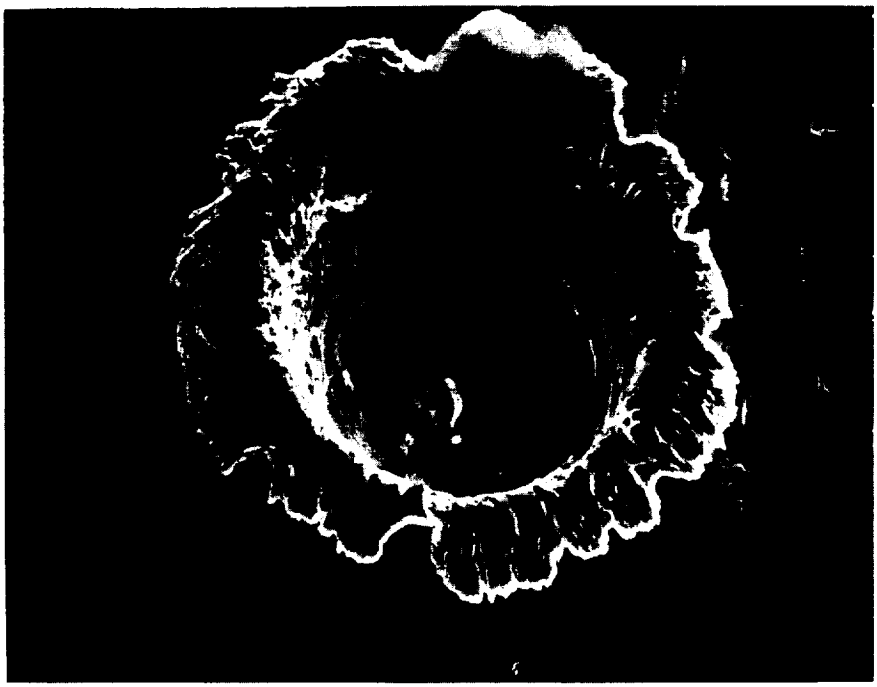
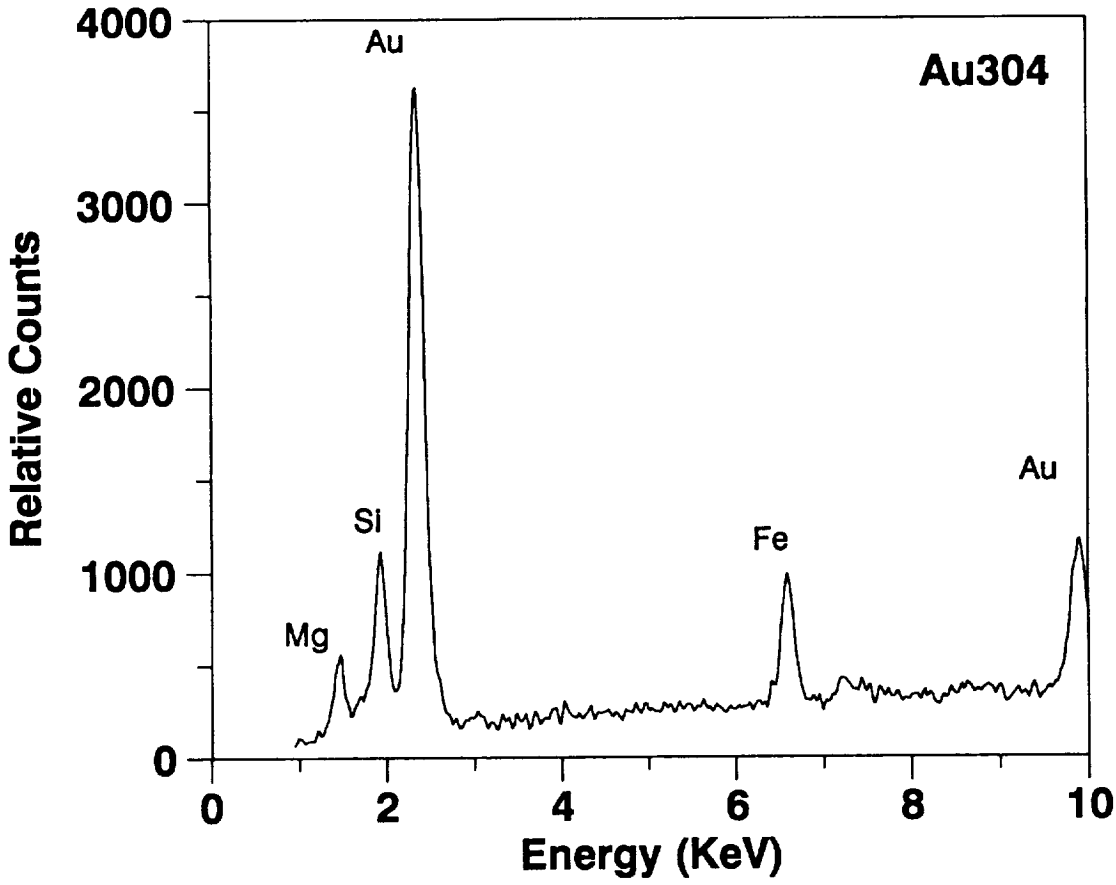


COMPONENT: EOOK
FEATURE: 304
CORE: LD-253

DIAMETER: 20 μm
ORIGIN: Natural



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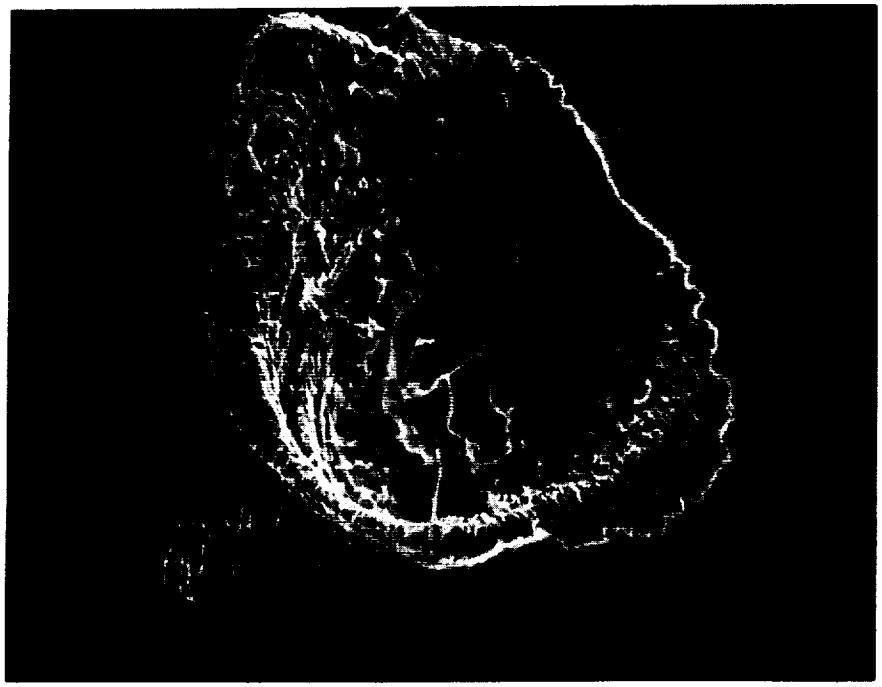
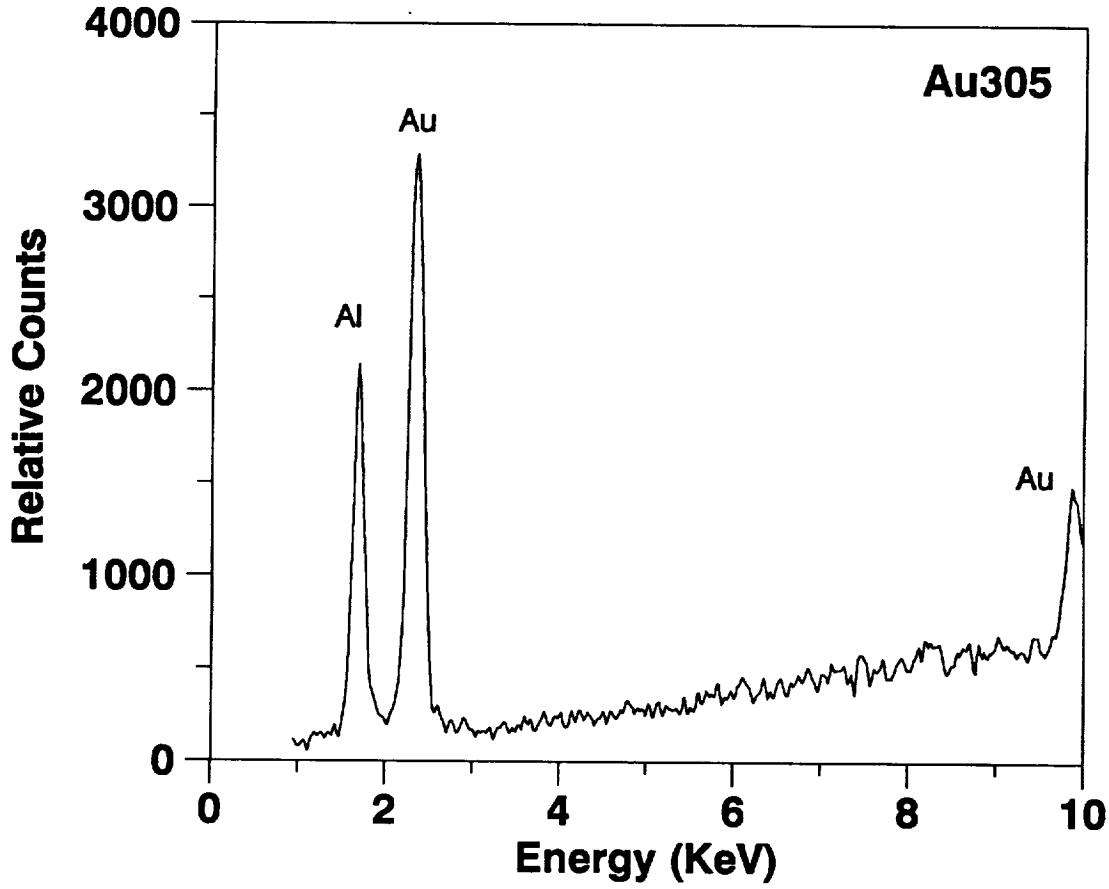


COMPONENT: EOOK
FEATURE: 305
CORE: LD-254

DIAMETER: 45 μm
ORIGIN: Man-made



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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>

14. SUBJECT TERMS
long duration exposure facility, low Earth orbit, hypervelocity projectiles, impact craters, cosmic dust particles

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