NMBM
OFR #393

Mobility of Heavy Metals in Soils and Tailings at the Hanover and Bullfrog Tailings Sites, Silver City, New Mexico

by

Tanya G. Baker

Thesis

Submitted in Partial Fullfillment of the
Requirement for the Degree of Master of Science
in Geochemistry

New Mexico Institute of Mining and Technology
Socorro, New Mexico

May, 1993

ACKNOWLEDGEMENTS

I would like to thank MRRC for funding this project and providing valuable information about the sites. I would also like to thank Dr. George Austin for his guidance and support. In addition, I would like to thank the NMBMMR Chemsitry Laboratory staff for conducting the analyses, and I would especially like to thank Lynn Brandvold for her invaluable advice and suggestions. Special thanks go to my husband, Ron, for his support and help with typing the manuscript.

ABSTRACT

The Hanover Mining District, located east of Silver City in southwest New Mexico, has been mined since at least the 1600's. The majority of production was for iron and base metals such as Cu, Zn, and Pb. The two sites of interest in this study are the Hanover and Bullfrog tailings piles. Tailings were produced from Zn-Pb sulfide-vein deposits. The main ore mineral at Hanover is sphalerite. Ankerite, specular hematite, pyrite, and pyrrhotite are common gangue minerals. The main ore minerals at Bullfrog (derived from three mines) are sphalerite and galena. Gangue minerals include quartz, pyrite, manganiferous calcite, chlorite, and rarely barite.

Movement of heavy metals from the tailings piles may occur by wind transport of metal-containing particles, fluvial transport, aqueous transport, and/ or plant uptake. To determine the mobility of heavy metals present at the sites, surrounding soils, vegetation, and surface water were sampled and analyzed. Soils were sampled at the surface and at depth to determine possible downward movement. Foliar samples were taken to determine metal concentrations in plants on and near the tailings. Surface water samples were taken from Hanover Creek above, adjacent to, and below the Hanover tailings to determine possible contamination from the tailings.

Surface soil samples taken in an area affected by wind-transported tailings material show slightly elevated Pb, Zn, and Cu concentrations above background. Concentrations of these metals drop to background levels below 2-4 cm in depth. Plant samples show little uptake of heavy metals even in samples taken on the edge of the tailings piles where wind transported material had engulfed the plant. Water samples taken adjacent to and below the Hanover tailings contain fewer total dissolved solids and lesser concentrations of the main ions SO_4 and Ca than those taken upstream of the tailings. This is probably due to the presence of calcium carbonate in the tailings material.

These results, together with the alkaline nature of the soils and arid climate of the southwest United States, indicate the probability of dissolved aqueous transport of heavy metals away from the tailings is low. It is recommended that the tailings be covered with topsoil and revegetated to decrease any effects the tailings may have on the surrounding environment.

TABLE OF CONTENTS

APPENDICES

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Published information on heavy metal concentrations in soils and/or water at mining sites does not adequately address the climate found in the arid southwestern United States (hereafter, referred to as Southwest). As a result, regulations and guidelines do not take this climate into consideration. Many abandoned mine sites in New Mexico are currently under consideration by the United States Environmental Protection Agency (EPA) for possible Superfund sites (e.g. Cleveland Mill site and CalWest). The Hanover and Bullfrog tailings piles are located in the Hanover Mining District (east of Silver City in southwestern New Mexico) which falls in this category. Reclamation of these tailings piles must consider the distribution of toxic materials in the tailings and the surrounding environment as well as the natural processes acting on the sites.

Purpose of the Study

Heavy metals such as lead (Pb) and cadmium (Cd) may have many different toxic effects on humans. For instance, Pb may have physiological and/ or neurological toxic effects such as restlessness, hyperactivity, confusion and impairment of memory, coma, and even death in humans (Fergusson, 1990.) The level of toxicity to humans depends on availability of those metals. This availability is determined by transport pathways (airborne dust, coating of edible food, and dissolution in surface and ground water), and by mobility of particles containing the heavy metals.

Site-specific pathways capable of transporting heavy metals from the site must be studied to determine whether metals are in fact being moved into the surrounding environment. Heavy metals in tailings may be released into the surrounding soil as a consequence of weathering. These metals may then be transported from the site, possibly as sediment by surface water, or in airborne dust particles.

The purpose of this study was to determine ion mobility and plant uptake of selected heavy metals near the Hanover and Bullfrog tailings piles in the Hanover Mining District secs. 21 and 32, T17S, R12W in the Santa Rita 7.5 minute Quadrangle (Fig. 1). Surrounding soils, tailings, plants, and surface water were analyzed because they represent major pathways for transportation of ions from the tailings.

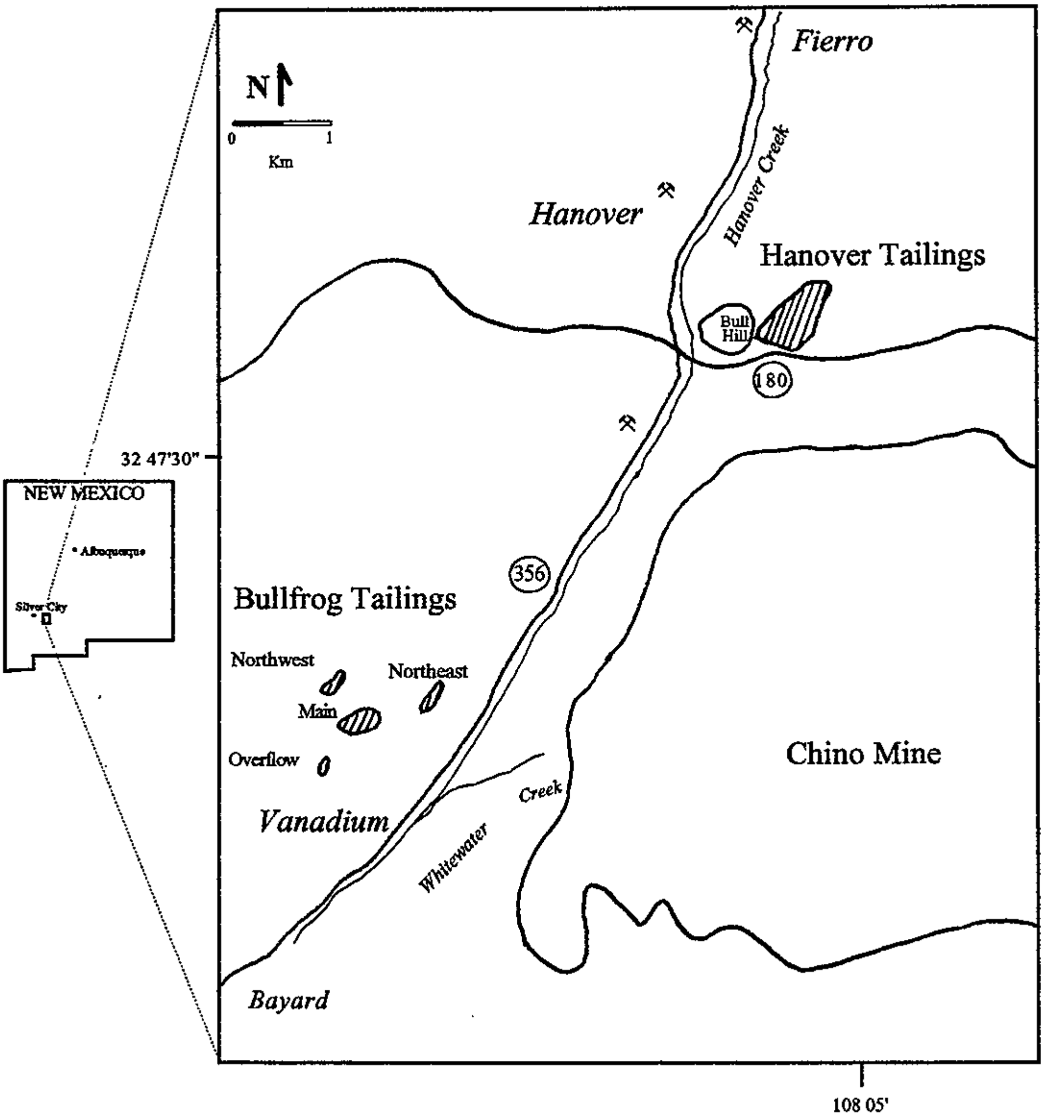


FIGURE 1. Location map of Hanover and Bullfrog tailings piles, major roads, and towns east of Silver City, New Mexico.

Previous Work

Processes and properties governing ion mobility

Understanding the processes governing the migration and plant availability of trace metals in soils is essential for predicting the environmental impact of metal-containing wastes. Metals and chemicals associated with tailings are of environmental concern because of the potential for pollution of surface and/or groundwater, off-site soil contamination by wind-transported material, uptake by vegetation, and bioaccumulation in food-chains (Chambers and Sidle, 1991).

Current guidelines for predicting mobility and availability are based on soil textural class or cation exchange capacity (CEC). However, many other soil properties may also be measured to predict mobility and availability of heavy metals. For instance, mobility of metals in soil is determined by the properties of the metal, the quantity and type of soil adsorption sites, and the concentration and type of complexing anions and competing cations in soil solution (Tyler and McBride, 1982). Other properties that may affect mobility and availability are soil organic matter (OM) content, pH, and soil chemical properties. Tyler and McBride (1982) found soil chemical properties to generally have a profound effect on the mobility of metals. Table 1 shows the heavy metal affinities for various soil components as determined by Tyler and McBride. The least mobile metals were observed in a soil with a relatively high pH, CEC, and exchangeable base content. The addition of $CaCO_3$ to soils (commonly referred to as liming) decreased mobility but not to the extent observed for a naturally nonacid soil. The order of mobility of heavy metals analyzed was found to be Cu<<Zn<Ni<Cd for

naturally nonacid soils and acid soils after liming. Their results show the ability of organic matter to restrict heavy metal movement and availability in naturally high-pH soils such as those found in the Southwest.

Table 1. Heavy metal affinity series for soil components (after Tyler and McBride, 1982).

Material	Relative affinity
Al oxides (amorphous)	Cu > Pb > Zn > Cd
Geothite	Cu > Pb > Zn > Cd
Fe oxides (amorphous)	Pb > Cu > Zn > Cd
Mn oxides	Cu > Zn
Fulvic acid (pH 5.0)	Cu > Pb > Zn
Humic acid (pH 4-7)	Zn > Cu > Pb
Humic acid (pH 4-6)	Cu > Pb > Cd > Zn

Soil Studies in Mined Areas

The ultimate fate of heavy metals in mine tailings is influenced by physical, chemical, and biological factors (Sidle et al., 1991). In addition to the factors previously mentioned, some other important factors that determine heavy metal distribution and availability are mechanical erosion and sediment transport, entrapment of sediment by vegetation and topographic depressions, and eolian processes. All of these are possible at abandoned mine sites found throughout the world, each with its own degree of contribution due to variation in climate. The threat of exposure is greatly reduced when the soil properties (both physical and chemical) and climate meet conditions which work to immobilize the metals.

Metal sulfides exposed to the atmosphere release metals and H_2SO_4 through both direct and indirect oxidation of the sulfide (Levy et al., 1992). As a result, surface waters that flow over or percolate through sulfide-rich mine spoil materials may contain elevated levels of sulfate, acidity, and dissolved metals. Accelerated oxidation of these sulfides increases the problem of effluent quality (Johnson and Eaton, 1980). In areas with high precipitation (e.g. the east coast of the United States or in the United Kingdom), the production of H_2SO_4 at mine sites is more likely than in semi-arid areas such as the southwestern United States. The following is a description of such a site in the United Kingdom.

A derelict Pb-Zn mine at Parc, near Llanwrst in North Wales, United Kingdom represents a site containing waste of similar composition to that found at the Hanover and Bullfrog sites. However, the difference in climate allows for offsite transport of heavy metals by surface water runoff. Heavy metal dispersal occurs through contaminated mine drainage waters and episodic erosion of an unstable tailings dam in the mine (Johnson and Eaton, 1980). The main stream has a high solute metal content derived from residual mineralization, surface tailings, and waste ore dumps before it goes through the mine. Surface soil samples analyzed from the derelict mine showed elevated Pb and Zn concentrations whereas the subsurface soil samples exhibited a quick drop in concentrations of these metals with depth.

To understand what governs ion mobility in soils it may be important to know what metal complexes are formed. Cu is predominantly associated with the organic fraction, whereas Cd, Pb, and Zn are predominantly associated with Fe and Mn oxides (Levy et al., 1992). In alkaline soils, mobility of Pb is controlled by the movement of Pb-bearing particles rather than its chemical transport in solution (Austin et al., 1993a). In a study done by Elliot et al. (1986), Pb and Cu remained in surface layers of soils contaminated from a smelting operation while Cd and Zn were more mobile and moved downward.

In a study similar to the present one, Sidle et al. (1991) investigated Cu, Zn, Cd, and Pb distribution in sediments within a Pb-Zn tailings pond in Alamitos Canyon near Pecos, New Mexico (Fig. 2).

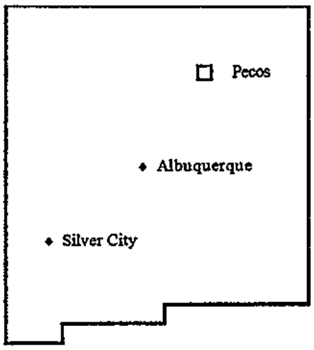


FIGURE 2. Location map of Pecos project in New Mexico (after Chambers and Sidle, 1991).

Concentrations of Pb elevated above background were found in surface soils near the Pb-Zn tailings pond (Sidle et al., 1991). The ratios of total metals in surface soils to metals in underlying or surface tailings were found to be higher for Zn and Cd than for Cu and Pb in the study. This reflects the greater solubilities of Zn and Cd. The relative order of cation mobility was found to be Cd > Zn > Cu > Pb. Lead is the least soluble of the metals analyzed. Pb most likely is not an environmental concern on a long-term scale because of its low solubility in nonacid soils. Its persistence should be long term, especially in nearly neutral pH surface deposits such as those found in the Southwest (Sidle et al., 1991). Preliminary sampling of stream sediments downstream of the tailings pond in the Pecos project showed metals moving off site due to erosion of tailings sediments and solution of metals.

Austin et al. (1993a) determined Pb distribution in soils near the Billing Smelter, in Socorro, New Mexico. The primary method of offsite transport of soils is by wind.

Soils analyzed from the Billing Smelter have the highest concentration of Pb in the finest size fraction of soil (Table 2). However,the depth of Pb contamination in relatively undisturbed areas was no more than a few inches. Similar results were observed in a study of the Cuba Road Smelter Site, Socorro, New Mexico (Brickell, 1991). In both cases, contaminated material was transported by wind; therefore, it is not surprising to find Pb in the finest size fraction of soil because airborne particles are generally very fine (< 10µm).

Table 2. Lead concentrations in sand-and-larger-, silt-, and clay-size fractions of soil (after Austin et al., 1993a).

SAMPLE	%SAND (63 µm to 2mm)	%SILT (2µm to 63µm	%CLAY (2µm)	Pb, sand fraction	Pb, silt fraction	Pb, clay fraction
GA90109	50	23	2	930	3,200	3,900
GA90110	38	27	3	820	2,700	4,300
GA90111	33	27	4	1,100	4,100	4,800
GA90112	40	28	3	750	3,300	3,800
GA90113	46	22	2	540	2,600	3,400
GA90114	42	23	3	860	2,600	4,100
GA90115	41	22	3	800	3,500	5,100
GA90116	42	23	3	700	2,800	4,500
GA90117	49	22	3	730	2,600	4,100
GA90118	46	24	2	710	3,400	5,700
GA90119	39	18	2	760	3,900	5,900
GA90120	47	24	3	740	4,900	2,200

Plant Uptake of Heavy Metals

Plants can take up heavy metals through the roots or through absorption by foliage. In the latter case, plants trap airborne dust in the crevices of their bark and this dust can become incorporated in woody tissue (Fergusson, 1990). Concentrations of metals in plants growing on tailings ponds are determined by several factors including concentrations and availability of metals in the soils, the metal species, and the plant species (Chambers and Sidle, 1991). Important factors in availability of Pb for plant root uptake are the chemical form of Pb, rainfall, drainage, soil pH, and acid-neutralizing capacity of soil. Root uptake of Pb should be less in an arid area that has poor drainage, alkaline soil, and soil with a high acid-neutralizing capacity (Austin et al., 1990).

Chambers and Sidle (1991) did a second study of the Pb-Zn tailings pond in Pecos, New Mexico. In this study, they were interested in the following aspects of the Pb-Zn tailings pond: 1) the relationships among depositional patterns, soil physical and chemical properties, and plant community attributes on the tailings pond and, 2) variation in Cd, Zn, Cu, and Pb concentrations among plant species and possible toxicity to plants and animals. Zn and Cd concentrations were found to be higher in deep-rooted plants (such as trees) than in shallow-rooted plants (such as grasses or cacti).

Plant material from the Billing Site in Socorro, New Mexico (Austin et al., 1993b) contained elevated Pb levels that increased as the amount of Pb in the soil increased. Plant species found at the Billings Site included sparse grasses, a few cacti, mesquite, rabbit bush, and creosote bush. Of these, rabbit bush showed the greatest increase of Pb levels.

Surface and Groundwater Contamination

When considering possible distribution pathways for mill waste containing heavy metals such as Pb, Zn, Cu, and Cd, it is important to look at the hydrologic system of the area. Metal-containing particles may be transported along the surface through runoff into surface water, such as a nearby creek, or they may transported downward by dissolution and may eventually reach the groundwater if the water table is shallow.

Much attention has been given to environmental affects to Whitewater Creek (Fig. 1) due to the Chino mine tailings ponds. The New Mexico Environment Department (NMED) conducted a site assessment of the area surrounding the Chino mine, including surface water and groundwater sampling, to determine affects of the addition of a new tailings pond at the mine. The study showed decreasing acidity of water in Whitewater Creek downstream of the Chino tailings pond due to reactions with carbonate and aluminosilicate minerals. Calcium from dissolution of these minerals reacts with sulfate in solution to form gypsum, which limits both the calcium and sulfate concentrations of these metals downstream.

Blood Pb Level in Cattle

One method of determining the extent of contamination surrounding a site is by measuring blood Pb levels in cattle grazing nearby. Neuman and Dollhopf (1992) conducted such a study to compare whole-blood Pb levels of cattle in Helena Valley, Montana, (near an active lead smelter) to Pb levels of cattle outside of the valley. Herds with high mean-Pb blood levels were located on surface soils containing high Pb concentrations. Herd blood concentrations were only moderately correlated to estimated vegetation Pb levels. Therefore, Neuman and Dollhopf conclude that soil with elevated Pb levels may be more important as a source of Pb for these cattle than Pb in their forage.

Other Studies Conducted in the Hanover Mining District

The Hanover Mining District has been studied extensively for its economic potential. In recent years, the New Mexico Environment Department has conducted feasibility studies of the area to determine the effect of a proposed tailings pond at Chino Mine on the surrounding environment (e.g. contamination of Whitewater Creek). Further, the Mining Remedial Reclamation Company (MRRC) has sponsored characterization studies of vegetation and tailings at the Hanover and Bullfrog tailings sites because it is responsible for possible environmental effects of these tailings. Descriptions of these studies follow.

The Arizona Remote Sensing Center, Office of Arid Lands Studies, University of Arizona, conducted a study of the vegetation of the Hanover and Bullfrog tailings sites using airborne multispectral video imagery. The identification of geobotanical and biogeochemical anomalies has developed into an operational tool in mineral and hydrocarbon exploration during the past two decades (Marsh and Kliman, unpubl. report for MRRC, 1992). Project objectives were to acquire airborne multispectral remote sensing data over Hanover and Bullfrog sites, as well as an undisturbed area in between, and to process and interpret the images to determine if a discernable spectral difference could be identified in vegetation over the mined area.

The initial interpretation from this study revealed that the vigor and density distribution of Pinon/Juniper class, and grass and brush cover is very variable in the Hanover-Bullfrog area. The cause is assumed to reflect both soil and water constraints as well as the historical activities of man. While a distinct decrease in the density of Pinon/Juniper cover surrounding the tailings piles at Hanover and Bullfrog was observed, no unique spectral evidence of stress on the vegetation was seen. The spectral response of the vegetation cover on the mine sites exhibits the same traits as area off the sites.

A characterization of the tailings piles (including chemistry, volume, area, and elemental distribution) was completed in 1992 (Walder, unpubl. report for MRRC, 1992). Surface samples of the tailings and windblown material were collected. Seventeen holes were drilled in the tailings using an auger (Figure 3; Table 3). The surface samples, windblown material, and core (sampled at 5-ft intervals) were analyzed for Zn, Cu, Pb, As, Se, Cd, Co, Ag, Ni, Bi, Zr, and Hg. Mineralogy of both light and heavy mineral separates was determined by XRD, and electron microprobe analysis of individual mineral grains was conducted.

Table 3. Drill hole depths (after Walder, unpubl. report for MRRC, 1992).

HOLE #	DEPTH (m)	HOLE #	DEPTH (m)
Hanover		B4	15.2
H1	27.1	B5	19.2
H2	34.1	B6	25.9
H3	17.7	**Bullfrog/NE**	
H4	19.8	B7	5.9
H5	22.9	B8	3.9
H6	22.3	**Bullfrog/NW**	
Bullfrog/Main		B9	5.5
B1	9.1	B10	14.6
B2	12.7	B11	7.2
B3	18.9		

The northwest (NW) and northeast (NE) tailings piles at Bullfrog (Figs. 1 and 3) show little to no alteration at the surface, while the Main and Overflow tailings piles (Figs. 1 and 3) show distinct surface alteration. This alteration is characterized by high concentrations of Pb, As, and Ag, and low concentrations of Zn and Cd (Walder, unpublished report for MRRC, 1992).

Surface tailings samples contain relatively low concentrations of Pb and Zn (370 and 2,240 ppm, respectively) but concentrations of these elements increase with depth (935 and 5,697 ppm, respectively; Fig. 4; Appendix B). Chemical variation with depth is attributed to ore variation (ore recovery changes) rather than leaching of metals through time after the tailings were deposited (Walder, unpubl. report for MRRC, 1992). The element distribution with depth indicates very little leaching has taken place since emplacement of the tailings. Oxidation of pyrite and the subsequent release of iron may produce acid if water were present in the system. Acid neutralizing potential (ANP) exceeds acid producing potential (APP) in all but two samples so it is unlikely that acid would be produced in the tailings.

The Hanover tailings showed no oxidation/alteration or metal leaching with depth. Pb and Zn concentrations were low in surface samples (280 and 3,550 ppm, respectively) but increased with depth (1,039 and 9,985 ppm, respectively; Appendix B). Calcite is present in quantities high enough to control pH and inhibit oxidation of sulfide minerals. ANP is greater than APP in all samples indicating that no acid will be generated by the tailings.

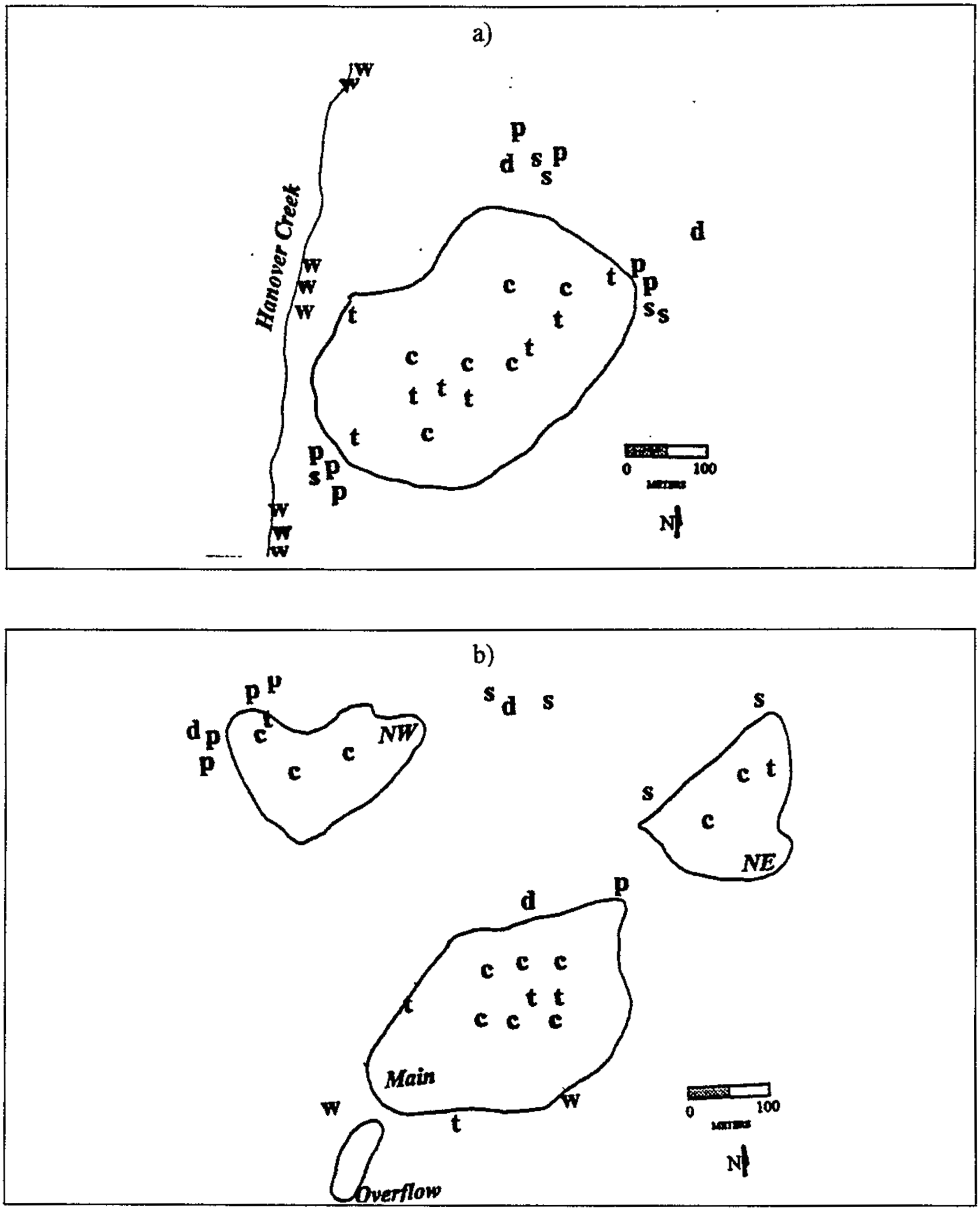


FIGURE 3. a) Sample locations and drill hole locations for the Hanover tailings site;
b) Sample locations and drill hole locations for the Bullfrog tailings site.

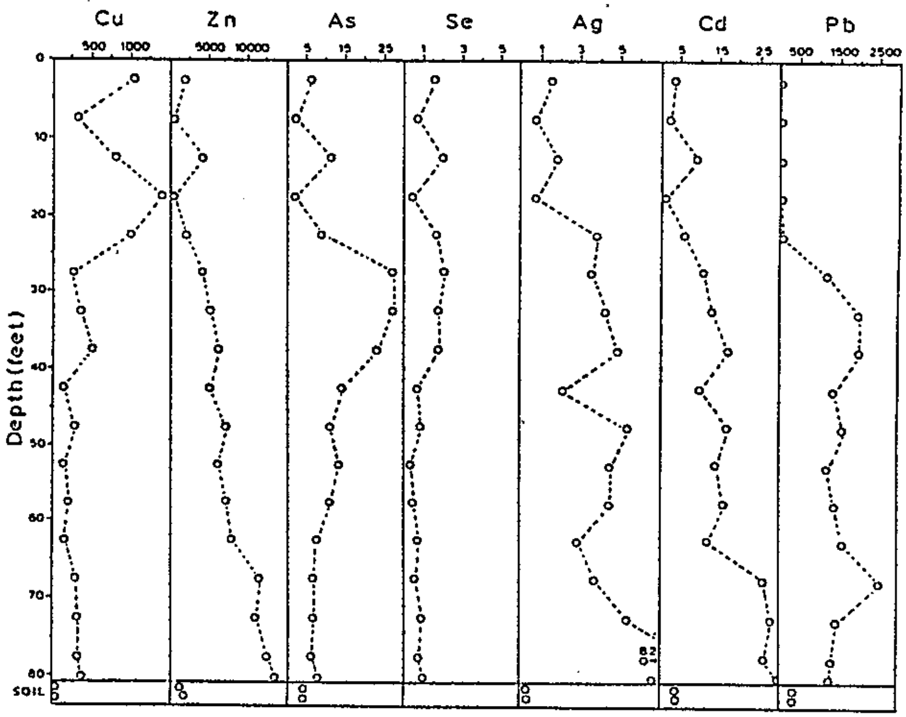


FIGURE 4. Elemental distribution with depth for drill hole, B6 (from Walder, unpubl. report for MRRC, 1992).

SITE DESCRIPTION

Mining History

Hanover Mining District has been mined since at least the 1600's. The majority of production was for iron and base metals such as Cu, Zn, and Pb. The principal nonferrous metal mines in the district from north to south were (1) the Continental, Sleeping Beauty, and Union Hill Complex at Fierro; (2) the Empire-Bull Hill zinc mines at Hanover; and (3) the Blackhawk-Hobo zinc mines complex between Hanover and Vanadium (NMED unpubl. report, 1988). Figure 1 shows the locations of these mines. The Continental Mine is scheduled to reopen in the summer of 1993.

Climate

The district lies in Grant County, New Mexico, in the southwestern part of the state. The climate in Grant County varies but may be considered as semi-arid because in most areas evaporation exceeds precipitation (Trauger, 1972). Precipitation is approximately 410 mm per year and occurs principally as late-afternoon thunderstorms during the summer months. Predominant wind direction is from the southwest. Winds blow about 16-32 kmph much of the year. Dust storms are frequent and 6-m-high dust clouds may be seen on and near the tailings piles.

Hanover

Geology

The underlying rocks are predominantly Magdelena Group limestones (Syrena and Oswaldo Formations) and a Tertiary rhyodacite porphyry plug (Bull Hill; Figs. 1 and 5). The limestones are intruded by quartz-diorite porphyry dikes and hornblende-quartz diorite sills of upper Cretaceous to lower Tertiary age, trending north-south (Jones et al., 1967).

Tailings

The Hanover tailings pile is located in Hanover, New Mexico, off New Mexico Highway 180 (NM-180). It occupies approximately 0.20 km^2 area and a volume of 1.8 million m^3 (Walder, unpubl. report for MRRC, 1992). The mill tailings are from the Empire Zinc mine. The ore from which the mill tailings were produced is from a massive sphalerite replacement deposit in limestone around the Hanover-Fierro stock (Jones, 1973). The main ore mineral is sphalerite with lesser amounts of chalcopyrite and galena (Jones, 1973). Andradite is the most abundant silicate mineral replacing limestone. Ankerite, specular hematite, pyrite, and pyrrhotite are common gangue minerals (Walder, unpubl. report for MRRC, 1992).

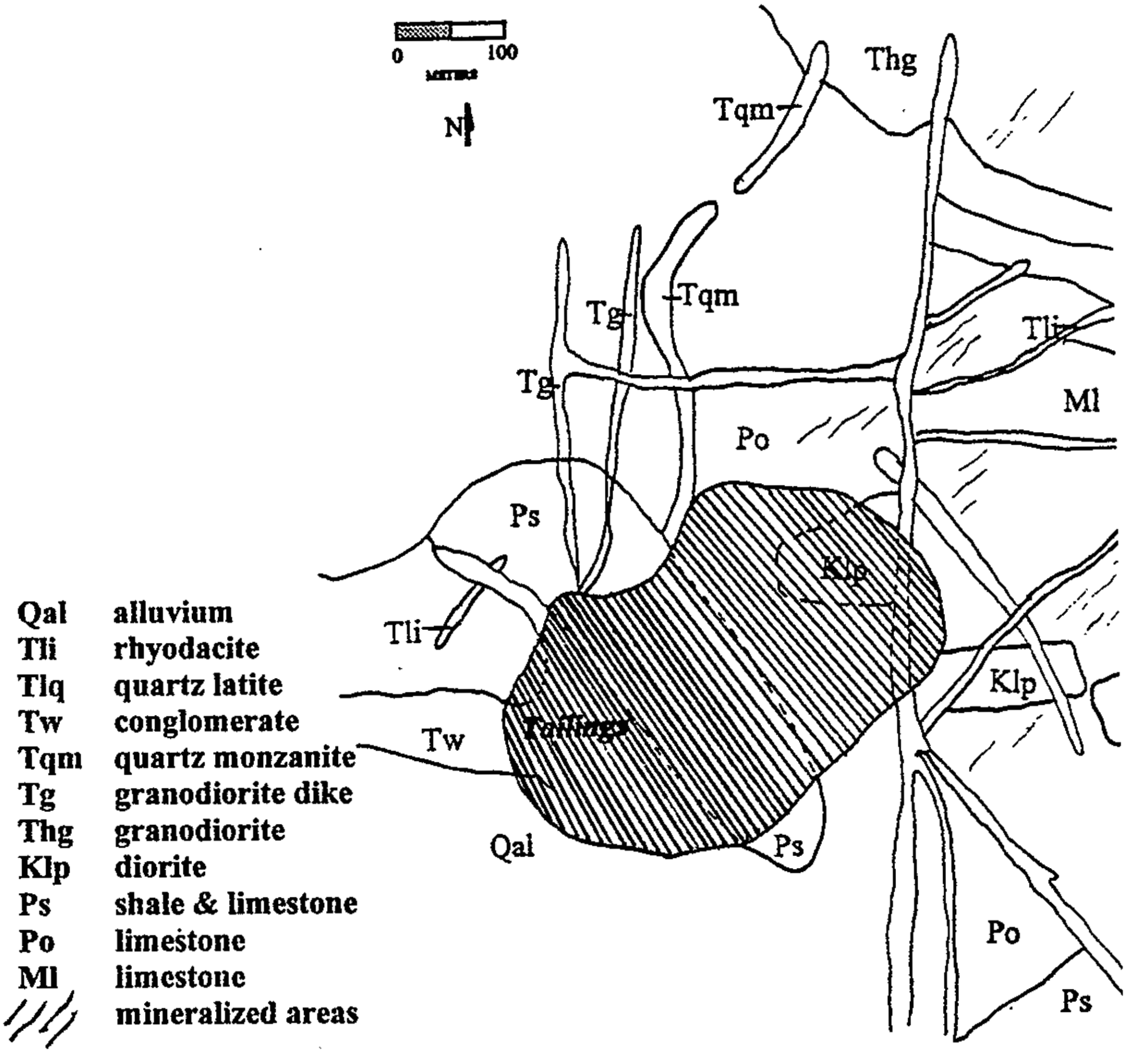


FIGURE 5. Geologic map of Hanover tailings site (after Walder, unpubl. report for MRRC, 1992).

The tailings are gray and resemble beach sand at the surface. The edges of the pile exhibit eolian structures such as ripple marks and well-developed dunes. The center of the pile is clay-rich at the surface, has polygonal cracks and lacks ripple marks. This is most likely due to the presence of standing water after times of significant precipitation. A wooden structure in the center of the pile is part of a distribution system for the slurry of tailings. Subsurface tailings are dark gray and exhibit a layering consistent with settling velocities of particles with different diameters based on Stoke's law. The sequence consists of a clay-rich layer at the surface, a silty layer below, and then a sandy layer at the base.

Vegetation

The region is covered with a mixed class of Juniper/Oak, Pinon/Juniper, and Grama/Tubosa/Mesquite shrub steppe (Marsh and Kliman, unpubl. report for MRRC, 1992; Fig. 6). Cactus species include prickly pear, cholla, and some yucca. Vegetation is sparse to the east of the tailings. A greater amount of Pinon/Juniper exists to the north, whereas the density of tree cover is quite variable on the crest and west side of Bull Hill. Brush cover appears to be greater south of NM-180 (Fig. 7).

FIGURE 6. Photograph of Hanover tailings and surrounding vegetation. View is due east. Note ponded water that accumulated on the tailings after snowmelt and runnoff.

FIGURE 7. Photograph of vegetation to the south of Hanover tailings. View is to the north, with the tailings in the middle distance.

Bullfrog

Geology

Underlying rocks at the Bullfrog site are hornblende quartz-diorite sills (Upper Cretaceous) cut by northeast-southwest trending dikes of granodiorite porphyry (Jones et al., 1973). Bedrock to the west of the tailings is sandstone of the Colorado Formation (Upper Cretaceous; Fig. 8). The sandstone and shale units of the Colorado Formation are found northeast of the tailings (Jones et al., 1973). The area directly to the northeast of the Main tailings pile is heavily mineralized.

Tailings

The Bullfrog tailings piles are southwest of the Hanover tailings near the townsite of Vanadium along New Mexico Highway 356 (NM-356). Three tailings piles and an overflow area are present at the Bullfrog site. These are Main, NW, NE, and Overflow. The respective estimated areas and volumes of these are: $\text{area}_{\text{Main}} = 0.054\ \text{km}^2$, $\text{volume}_{\text{Main}} = 0.065$ million m^3, $\text{area}_{\text{NW}} = 0.025\ \text{km}^2$, $\text{volume}_{\text{NW}} = 150{,}000\ \text{m}^3$, $\text{area}_{\text{NE}} = 0.017\ \text{km}^2$, $\text{volume}_{\text{NE}} = 42{,}000\ \text{m}^3$, $\text{area}_{\text{Overflow}} < 0.003\text{km}^2$, $\text{volume}_{\text{Overflow}} = 3{,}800\ \text{m}^3$ (Walder, unpubl. report for MRRC, 1992). The tailings were derived from several Zn-Pb-Cu mines along the Hobo and Slate Fault Zones containing argentiferous Zn-Pb sulfide veins (Schmitt, 1939; Jones, 1973). The principal ore minerals were sphalerite galena with accessory amounts of chalcopyrite. The gangue minerals include quartz, pyrite, manganiferous calcite, and chlorite (Walder, unpubl. report for MRRC, 1992).

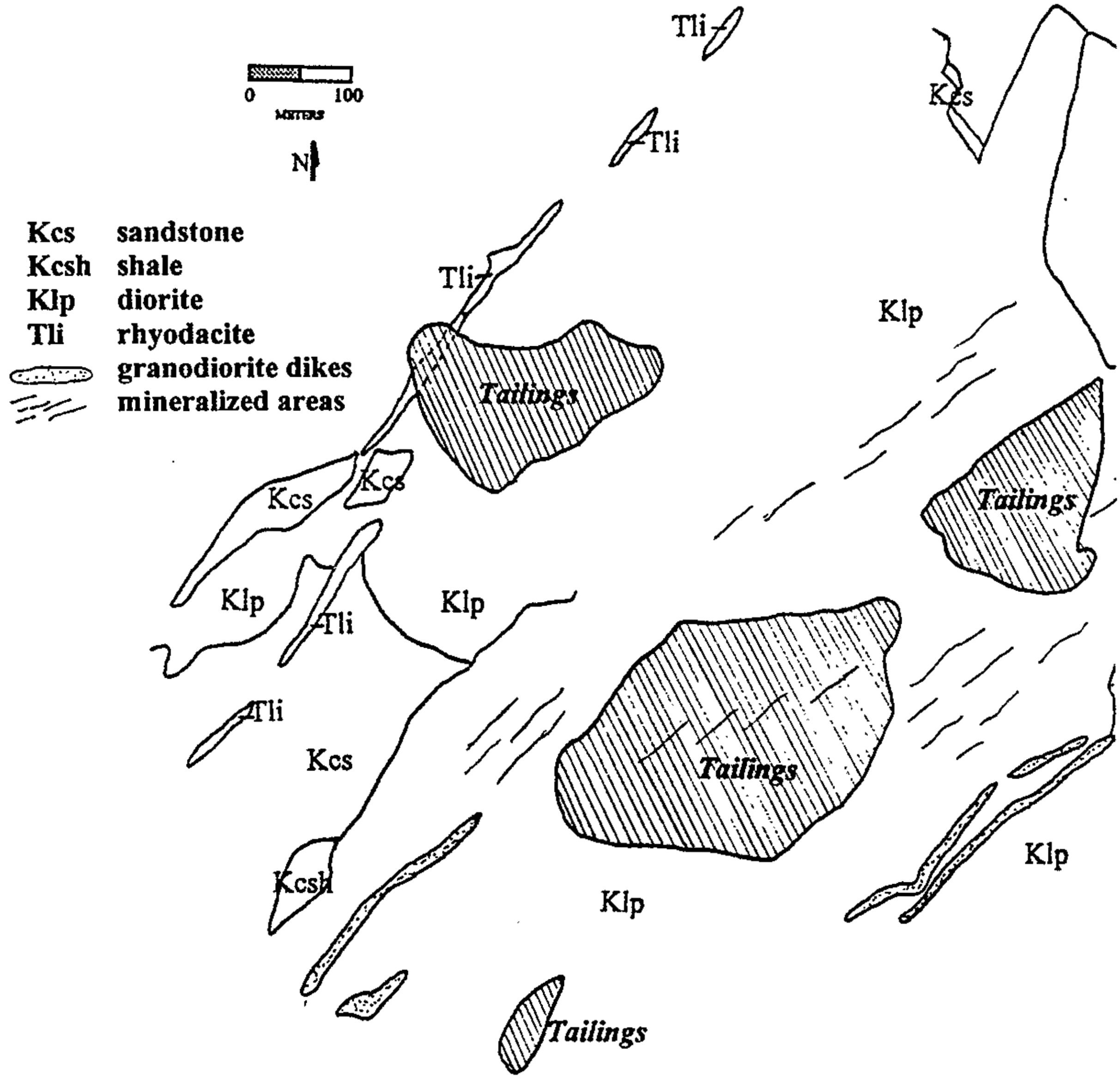


FIGURE 8. Geologic map of Bullfrog tailings site (after Walder, unpubl. report for MRRC, 1992).

The top of the Main tailings pile is similar in appearance to the top of the Hanover tailings pile. However, white precipitates have formed at the surface along the sides of the pile along with an orange color most likely due to pyrite oxidation (Fig. 9). These precipitates seem to form on the outter edges of clay-rich horizons. Water percolating downward from the surface reaches these clay-rich layers and migrates laterally until it reaches the edge of the tailings pile (Fig. 10). Evidence of the presence of clay-rich layers (possibly only lenses) is seen in drill core taken from the piles and also at the surface.

FIGURE 9. Photograph showing location of orange oxidation on the Main tailings pile at the Bullfrog site. View is to the north.

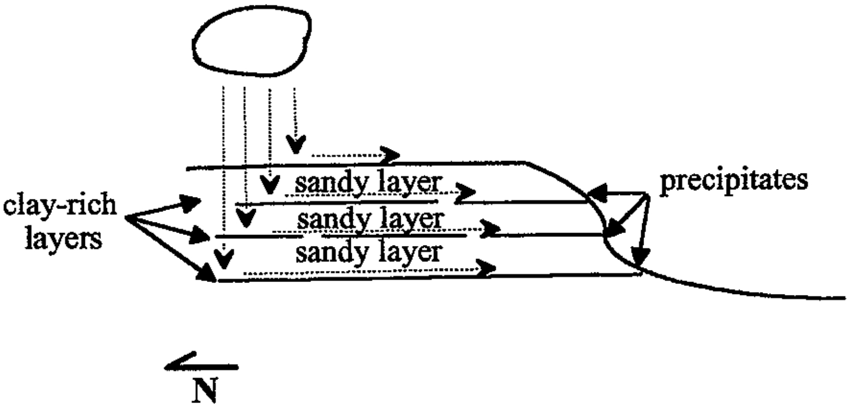


FIGURE 10. Diagram of water movement through the Main tailings pile at the Bullfrog site. (Note clay-rich layers are probably lenses rather than continuous layers.)

The NW and NE tailings piles show very little oxidation or formation of precipitates at the surface. Dune structures and ripple marks are evidences of eolian transport of tailings material; the tailings have been extended slightly to the northeast due to eolian transport of smaller particles (Fig. 11). Plants that have been engulfed in this material are evidence of this transport.

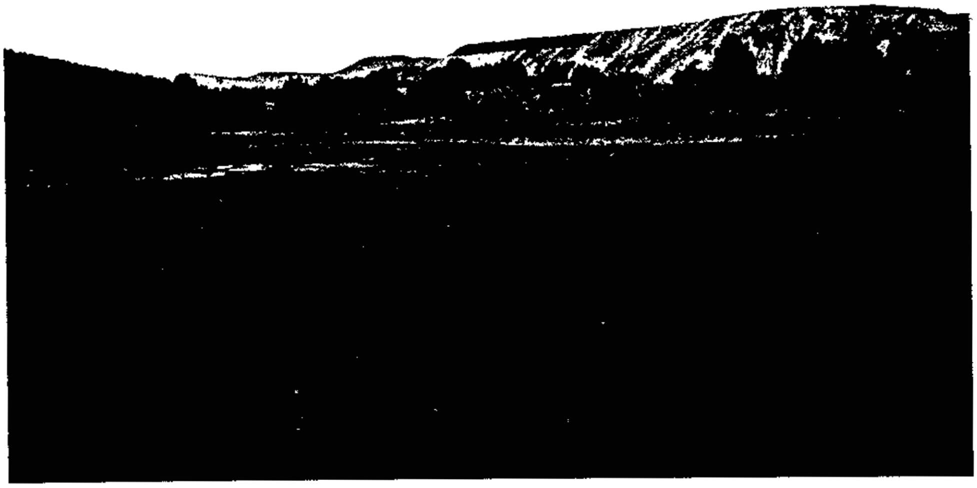


FIGURE 11. Photograph of the surface of the Main tailings pile at the Bullfrog site, looking northeast. Ripple marks are present in the foreground and dunes are located in the middle ground. Chino mine is located in the background.

Vegetation

Vegetation consists of predominantly Pinon/Juniper, and Juniper/Oak classes (Marsh and Kliman, unpubl. report for MRRC, 1992). Cacti species found near the tailings include cholla and prickly pear. Dense vegetation is found along the north and northwest edges of the NW tailings, presumably because the pile is shallow along these edges and allows for continued growth of existing vegetation (Fig. 12). Reduced

Pinon/Juniper cover density is observed on the west side of the pile. No vegetation exists on the Main tailings or the NE tailings.

FIGURE 12. Photograph of the NW tailings pile at the Bullfrog site, looking north. Note vegetation is living and appears healthy even though tailings material surrounds it.

METHODS

Sampling Procedures and Preparation

Soils

Two types of soil samples were taken: surface samples (0-1 cm in depth) and pit samples (Fig. 3). A shovel and rock hammer were used to remove surface samples by the "grab" method. Approximately 0.5 kg of surface material was removed. Samples were also taken from pits approximately 20 cm deep. Depths of the pits were measured and samples taken from the pit walls with a pick and small hand shovel.

Soil samples were dried under heat lamps for 24 hrs and placed in paper cartons for storage. Approximately 20 g of material from each sample was split (using a Jones splitter) and sent to the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) Chemistry Laboratory for analysis. Two g from each sample were split and crushed for x-ray fluorescence (XRF) and x-ray diffraction (XRD) analyses.

Tailings

Tailings material was sampled in three types of locations: surface material from the tailings piles, material at depth (core), and wind-blown material from the area to the northeast of Hanover tailings, and to the northeast of the Main tailings and NW tailings at the Bullfrog site. Surface material (0-1 cm in depth) was collected using the same method as for surface soil samples. Core was collected with a 1.5-m-long hollow-stem auger. The core diameter was 6.25 cm. Wind-blown material was collected from the soil cover off of the tailings piles in the direction of the predominant wind (to the northeast). Material was collected using a small hand shovel.

Surface samples and wind-blown material were air dried and placed in paper cartons for storage. As with the soil samples, 20-g splits were submitted to the NMBMMR Chemistry Laboratory for analysis and 2-g splits were used for XRF and XRD analyses.

Plants

Samples of foliage and branches from various plant types were removed with a knife and placed in plastic bags. These were taken from undisturbed areas, mineralized areas, and from plants which were engulfed by the tailings material (Fig. 3). Plants sampled include cholla and prickly pear cacti, juniper, pinon, and pine trees, and grass.

Plant material was washed to remove dust and other debris, and air dried. Samples were cut into sections and approximately 150 g of material per plant were split from the whole. This split was placed in a weighed evaporating dish and placed in a 375°C muffle furnace for 1 hr and then 550°C for 3 hrs. The dishes were removed from the furnace and allowed to cool to room temperature. The evaporating dish, plus the ash, was weighed to determine the percent ash. The ash was then submitted to the NMBMMR Chemistry Lab for chemical analysis.

Water

Samples were taken from Hanover Creek, a pool of water on the main tailings pile at the Bullfrog site, and below a leaky pipe also located on the main tailings pile at the Bullfrog site (Fig. 3). Water from the leaky pipe originates from the Continental mine north of the Hanover tailings site. For each water sample collected, two plastic bottles were filled. One bottle had been rinsed in concentrated nitric acid and one rinsed in deionized water. Approximately 3-5 ml of concentrated nitric acid were added to the water placed in the acid-rinsed bottle to preserve the metal ions in solution. Nothing was added to water in the deionized water-rinsed bottle. Samples were not filtered in the field because the necessary equipment was not available. Care was taken, however, to not disturb sediments in the sample area. Samples should therefore contain only dissolved solids and no sediments. Both bottles of each sample were given to the NMBMMR Chemistry Laboratory for analysis.

Analyses

Several procedures were utilized to determine the nature of the soils and tailings. These include atomic absorption spectrometry (AA) for heavy metal concentration, acid producing potential determination (hydrogen peroxide/titration method), acid neutralizing potential determination (HCl/titration method), x-ray diffraction (XRD) for bulk mineralogy, x-ray fluorescence (XRF) for bulk chemistry, and soil pH. Plant samples were analyzed for the elements Pb, Cu, Zn, and Cd using AA. Water samples were analyzed for major ions, pH, conductivity, and total dissolved solids using AA (cations), high-pressure ion chromatography (HPIC or IC; anions), and a pH meter. Lead, Cu, Zn, and Fe concentrations were also determined using AA. These analyses are described in detail below.

Atomic Absorption

The machine used is an Instrumentation Laboratory, Inc., Video 12 aa/ae spectrophotometer. The light sources used for Pb, Cu, Zn, and Cd were hollow cathode lamps. The lamp current, wavelength, and slit width vary with the element. A mixture of air/acetylene was used in the burner head for all elements analyzed.

Soil, tailings, and core samples were ground mechanically for 15 secs. From 0.5 to 1 g of the resulting powder of each sample was then given to the NMBMMR

Chemistry Laboratory for chemical analysis. Plant samples were ashed and the resulting ash was treated in the same manner as the soils and tailings. Soil, tailings, core, and plant samples were analyzed for Pb, Cu, Zn, and Cd using AA.

High-Pressure Ion Chromatography

Determination of anions in water samples was conducted on the Dionex 4000i IC equipped with a Conductivity Detector, and UV-Vis (for determination of NO_3^- in the presence of SO_4^{2-}). Samples were filtered through 0.22 μm filter paper and run through a 4 x 250 mm analytical column with a CO_3/HCO_3 eluent. A Dionex Integrator 4270 was used to calculate concentrations of the anions.

Acid Neutralizing Potential

This technique is used to quantify neutralizing bases, including carbonates, present in a rock. It treats the sample with a known excess of hydrochloric acid, allowing the sample to stand covered overnight to ensure complete reaction, and to determine the unconsumed acid by titration with a standardized base (Smith et al., 1974). Results are reported as tons $CaCO_3$/100 tons sample.

Net Acid-Producing Potential

Samples were treated with HCl to remove carbonates and sulfates. Hydrogen peroxide (H_2O_2) was added and the reaction was allowed to go to completion. Unreacted H_2O_2 was then driven off. Samples were washed with distilled water, brought to a volume of 100 ml, and heated to drive off any dissolved CO_2. NaOH (sodium hydroxide) was used to titrate the solution. The amount of $CaCO_3$ required to neutralize the acid produced is calculated and reported as tons $CaCO_3$/100 tons sample.

X-ray Diffraction

To determine bulk mineralogy, XRD of randomly oriented powder samples was completed. This method identifies mineralogy of samples. Approximately 1 g of sample was split and ground to pass through a #70 sieve.

One of two x-ray diffractometers was used. The Norelco diffractometer was used to x-ray soil and surface tailings samples. The machine settings were 40 kV, 25 mA, scan speed of 2° 2θ/min, and a chart speed of 1 inch/min. Core samples were analyzed with the Rigaku diffractometer at 40 kV (voltage), 25 mA (current), and a scan speed of 2° 2θ/min.

X-ray fluorescence

XRF was used to determine general chemistry of selected samples. A Rigaku 3064 XRF machine was used to analyze major elements such as Ca, Fe, Mn, Zn, Cu, and Pb. An Rh window tube was used in this analysis. The machine settings were 60 kV , 45 mA, scan speed of 2° 2θ/min, and a chart speed of 20 mm/min. This analysis is to verify data obtained by AA and XRD.

pH

The sample first must be classified as calcareous or noncalcareous. If it is noncalcareous, 10 g are weighed into a 50-ml beaker, along with 20 ml of deionized water. The suspension must be stirred several times during the next 30 min. The suspension must stand for about 1 hr to allow most of the suspended clay to settle out from the suspension. The electrodes are then inserted into the sample solution and the pH is measured. If the sample is calcareous, 10 g are placed in a 50-ml beaker and 20 ml of 0.01 M $CaCl_2$ solution are added. The remainder of the procedure is the same as for noncalcareous samples (J. Verplough, personal communication, 1992).

RESULTS

Hanover

Tailings

H001A through H009 (except H006) are surface tailings samples (Fig. 3). Sample types included sandy, clay-rich, and wind-blown materials. See Appendix A for sample descriptions. Lead ranges from 124 to 840 ppm (Fig. 13). Only two samples contain Pb above 500 ppm (EPA-determined lower limit for Pb in soils); H001A, 660 ppm and H005, 840 ppm. H001A is a clay-rich material taken at the surface near the center of the pile, and H005 is a sandy sample taken approximately 6 m southwest of the structure located in the center. Copper concentrations range from 199 ppm (H002) to 1400 ppm (H005; Fig. 13). Zinc concentrations are high relative to Pb and Cu (Fig. 13). The range is from a low of 1200 ppm (H004) to a high of 8300 ppm (H008). No EPA-determined limits for Cu and Zn content in soils have been set to date. This is probably because Cu and Zn are not as likely to have toxic effects on public health. Cadmium concentrations were quite low relative to Pb, Cu, and Zn. H003 contained the lowest amount with 1 ppm and H008 contained the highest with 19 ppm. See Appendix A for complete chemical analyses.

Bismuth and cobalt tend not to be solubilized as easily as Pb, Cu, Zn, and Cd. Bismuth concentrations range from 34 to 57 ppm (H009 and H002, respectively.) Cobalt ranges in concentration from 1.9 to 85 ppm (H003 and H002, respectively.)

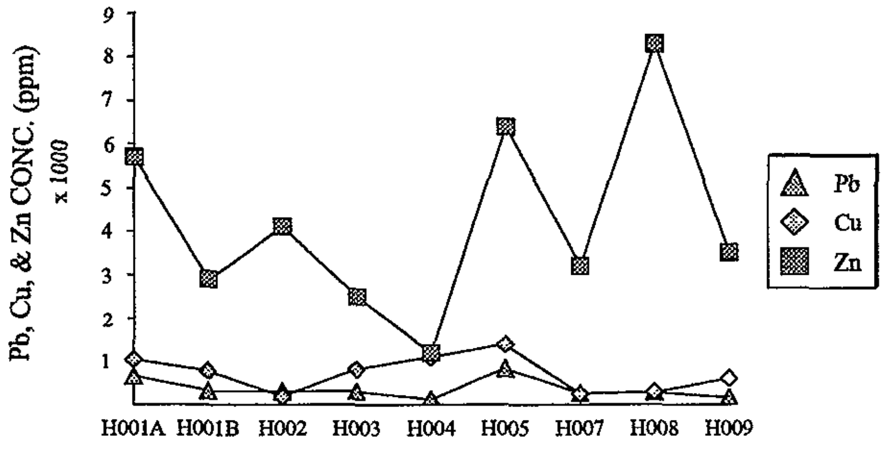


FIGURE 13. Lead, copper and zinc concentrations in surface tailings samples at the Hanover Site.

Net acid producing potentials for surface tailings are all negative. Samples H001A and H002 have the smallest NAPPs, -17.1 and -18 tons $CaCO_3$/100 tons sample, respectively (Fig. 14).

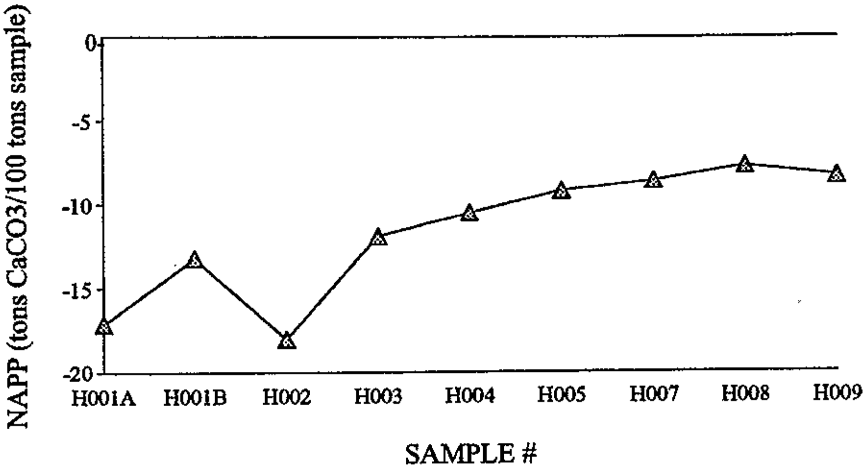


FIGURE 14. NAPPs for surface tailings samples.

Tailings core

Hole, H1 was sampled extensively in the tailings up to 3 m above the underlying rock material. Lead concentrations range from 440 ppm at a depth of 24-24.3 m to 750 ppm at a depth of 25.6 -25.9 m. Underlying rock is represented in sample H043. Minerals consist chiefly of analcime and Ca-feldspar. Concentrations of Pb, Cu, and Zn are lower than in the tailings directly above (H042) the rock (Table 4). Net acid producing potentials are negative indicating low probability of acid production in this environment (Fig. 15).

Table 4. Lead, copper, and zinc concentrations of rock material and overlying tailings.

	Depth (ft)	Depth (m)	Pb (ppm)	Cu (ppm)	Zn (ppm)
H042 (tailings)	87-88	26.5-26.8	690	330	5,600
H043 (igneous)	88-90	26.8-27.4	92	150	940

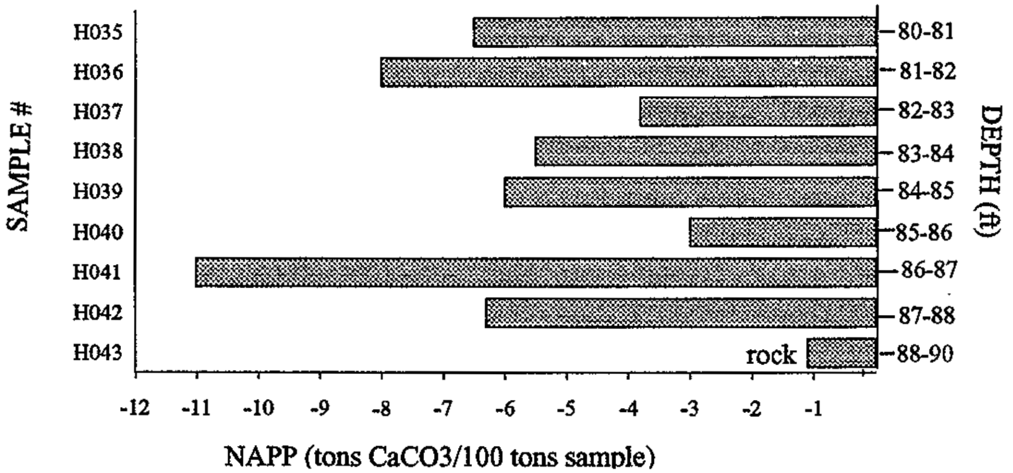


FIGURE 15. NAPP for hole, H1.

Underlying rock in H2, H3, H4, and H6 is shale and limestone. The minerals in rocks in these holes are quartz, Ca-feldspar, calcite, illite, smectite, and kaolinite. Metal concentrations are much lower in the rocks than in the tailings directly overlying them (Table 5). H6 shows a significant decrease in concentrations of Pb, Cu, and Zn in the underlying rock material (Table 5).

Table 5. Lead, copper, and zinc concentrations of rocks and tailings directly overlying them in H2, H3, H4, and H6.

SAMPLE #	HOLE/ DEPTH (m)	Pb (ppm)	Cu (ppm)	Zn (ppm)
H048, tailings	H2/ 34-34.3	1,700	5,200	7,100
H056, rock	H2/ 34.3-34.8	398	102	5,100
H057, rock	H2/ 34.8-35.1	382	165	5,300
H051, tailings	H3/ 17.4-17.6	8,700	300	6,900
H052, rock	H3/ 17.6-17.7	393	60	2,300
H053, rock	H4/ 18.3-18.9	174	58	1,600
HO54, rock	H4/ 18.9-19.5	81	40	1,000
H055, rock	H4/ 19.5-19.8	48	50	570
H058, tailings	H6/ 21.3-21.5	1,400	670	4,900
H059, rock	H6/ 22.6-23.2	60	73	224
H060, rock	H6/ 23.2-24.4	42	58	180

If metals were being leached downward, Zn concentrations should be higher with depth because of the greater mobility of Zn over Pb. A decrease in Zn concentration with depth suggests an environment not capable of solubilizing heavy metals. This environment is most likely alkaline as evidenced by NAPPs and pH (Table 6).

Table 6. Soil pH of core rocks and tailings.

SAMPLE #, HOLE #	SOIL pH
H042, H1	7.4
H043, H1	7.6
H048, H2	8.4
H056, H2	9
H057, H2	8.6
H051, H3	7.7
H052, H3	7.7
H053, H4	7.8
H054, H4	7.7
H055, H4	7.5
H058, H6	7.8
H059, H6	8.2
H060, H6	8.2

Soils

Surface samples were taken from an undisturbed area (Bull Hill, H029), in an arroyo to the north of the tailings (H018 and H019), and on the hillside to the northeast of the tailings in an area showing evidence of wind-blown tailings deposition (H012 and H013). Soils consist of quartz, illite, smectite, and/or illite-smectite mixed-layered (I/S) clay minerals, with minor amounts of feldspar, calcite, and rarely, apatite (Appendix C).

Heavy metal content varies between the undisturbed area and the areas affected by wind-blown tailings material whereas ANPs and NAPPs are similar to those for surface tailings samples. Undisturbed soils contain lesser amounts of Pb, Cu, and Zn than soils to the north of the tailings pile and to the northeast of the tailings pile (Table 7). ANPs range from 0.0 to 9.1 tons $CaCO_3$/100 tons sample (% $CaCO_3$) and NAPPs range from -5.9 to 1.7 tons $CaCO_3$/100 tons sample (% $CaCO_3$; Table 8).

Table 7. Lead, copper, and zinc concentrations for undisturbed soils, soils from the area to the northeast, and soils to the north.

SAMPLE #, location	Pb (ppm)	Cu (ppm)	Zn (ppm)
H029, Bull Hill	100	97	1,300
H012, northeast	170	435	3,900
H013, northeast	300	425	4,300
H018, north	740	350	9,800
H019, north	870	200	4,400

Table 8. Acid neutralizing potentials and net acid producing potentials for surface soils near the Hanover tailings.

SAMPLE #, location	ANP (% $CaCO_3$)	NAPP (% $CaCO_3$)
H029, Bull Hill	4.8	1.7
H012, northeast	9.1	-5.9
H013, northeast	8.3	-5.4
H018, north	0	1.3
H019, north	7.7	1.1

Subsurface soils from pits dug to the north and to the northeast of the tailings exhibit a distinct decrease in Pb concentration from that found at the surface (Fig. 16). Acid neutralizing potentials range from 7.5 to 11.6 tons $CaCO_3$/100 tons sample (% $CaCO_3$) and NAPPs range from -11.4 to -7.5 tons $CaCO_3$/100 tons sample (% $CaCO_3$; Table 9).

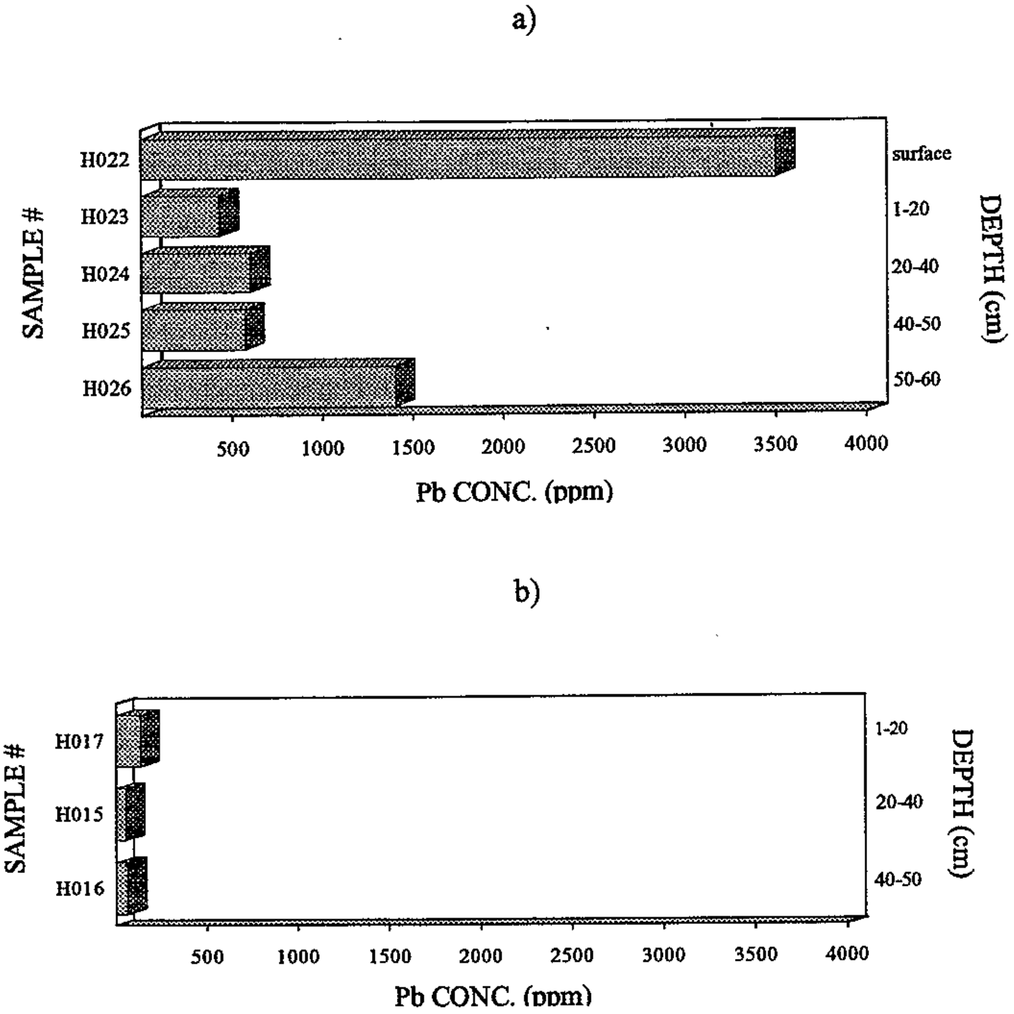


FIGURE 16. a) Pb in northeast pit, b) Pb in north pit.

Table 9. ANP and NAPP for subsurface soils near the Hanover tailings site.

SAMPLE #	ANP % $CaCO_3$	NAPP % $CaCO_3$
north pit		
H017, 1-20 cm	11.1	-11
H015, 20-40 cm	11.6	-11.4
H016, 40-50 cm	10	-9.8
northeast pit		
H022, 0-1 cm	11.6	-8.9
H023, 1-20 cm	9.3	-8
H024, 20-40 cm	9.3	-9.2
H025, 40-50 cm	8.9	-8.8
H026, 50-60 cm	7.5	-7.5

Plants

Pinon and pine trees, cholla and prickly pear cacti, and grass foliar samples were taken near soil samples so that a comparison of soil Pb to plant Pb could be made. It was difficult to remove soil from the grass samples, so concentrations may not reflect plant uptake of heavy metals only. Lead concentrations range from 0.5 ppm (H028, pine) to 5.95 ppm (H021, grass). The highest Pb values are found in the two grass samples (Table 10).

Table 10. Lead values of plant samples taken near the Hanover tailings site.

SAMPLE #	DESCRIPTION	LOCATION	Pb (ppm)
H010	grass	northeast of tailings	1.98
H020	cholla cactus	north of tailings	0.7
H021	grass	same	5.95
H027	cholla cactus	Bull Hill	0.7
H028	prickly pear cactus	same	0.5
H030	pinon	same	0.37
H031	pine	same	0.33

Lead concentration in a cholla cactus sampled in an undisturbed area (H027, Bull Hill) is approximately the same as that found in a cholla cactus sampled north of the tailings pile (H020). The deep-rooted plants (pinon and pine trees) contain less Pb and greater amounts of Cu than the shallow-rooted plants (cholla and prickly pear cacti). A comparison of Pb values in the plants to Pb values in the soils is shown in Fig. 17.

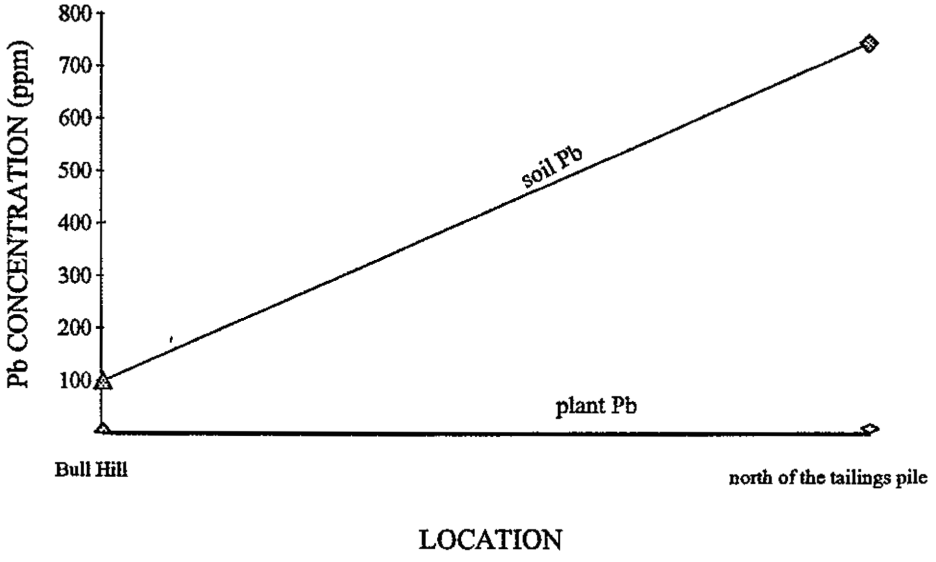


FIGURE 17. Lead concentrations in 2 soils and 2 plants from an undisturbed area (Bull Hill) and an area to the north of the tailings pile.

Surface Water

Hanover Creek lies between the Hanover tailings and state highway 356 (Fig. 1). Tailings can be found covering much of the area including the Hanover Creek bed near the Hanover tailings pile (Fig. 18).

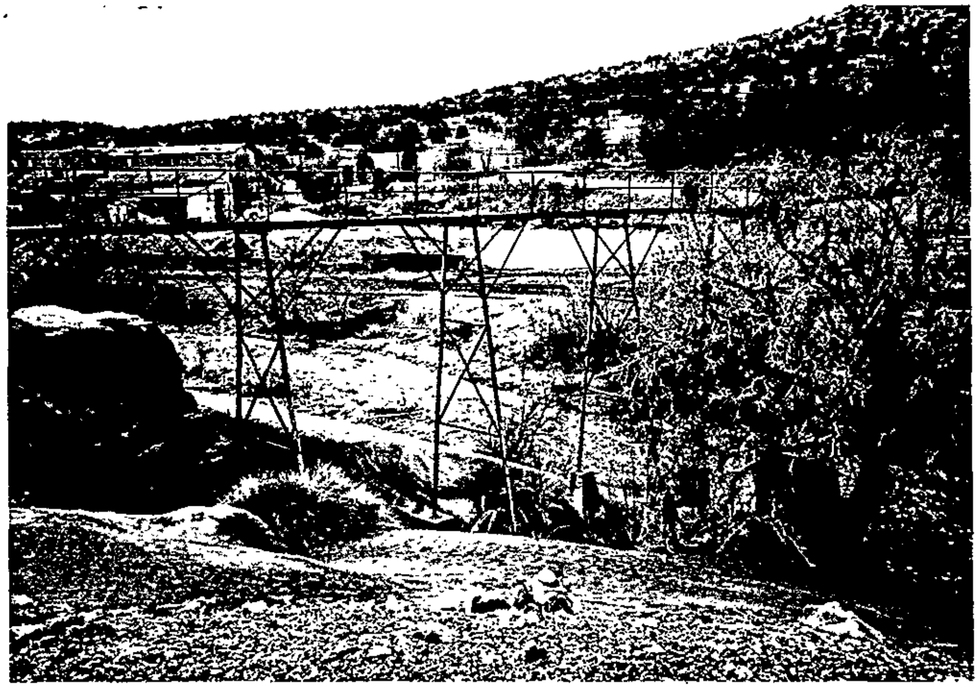


FIGURE 18. Photograph showing tailings on either side of Hanover Creek.

Concern of possible contamination of the creek led to three occasions of water sampling each with a different rate of flow (sample locations in Fig. 3). A water sample was taken from the creek adjacent to the tailings (H014) in May, 1992. In August, 1992, three additional samples were taken. H032 was taken upstream of the tailings, H033 was taken in the same area as H014, and H034 was taken downstream of the tailings, south of state highway 180. Six surface water samples were taken in January, 1993. These were: H061 (headwaters), H062 (upstream, same location as H032), H063 (upstream), H064 (adjacent, same location as H014 and H033), H065 (downstream), H066 (down stream, same location as H034). Calcium and sulfate are the major ions present in all samples (Appendix A). Concentrations show a slight decrease downstream of the tailings in samples taken in August; concentrations remain relatively the same in samples taken in January (Fig. 19).

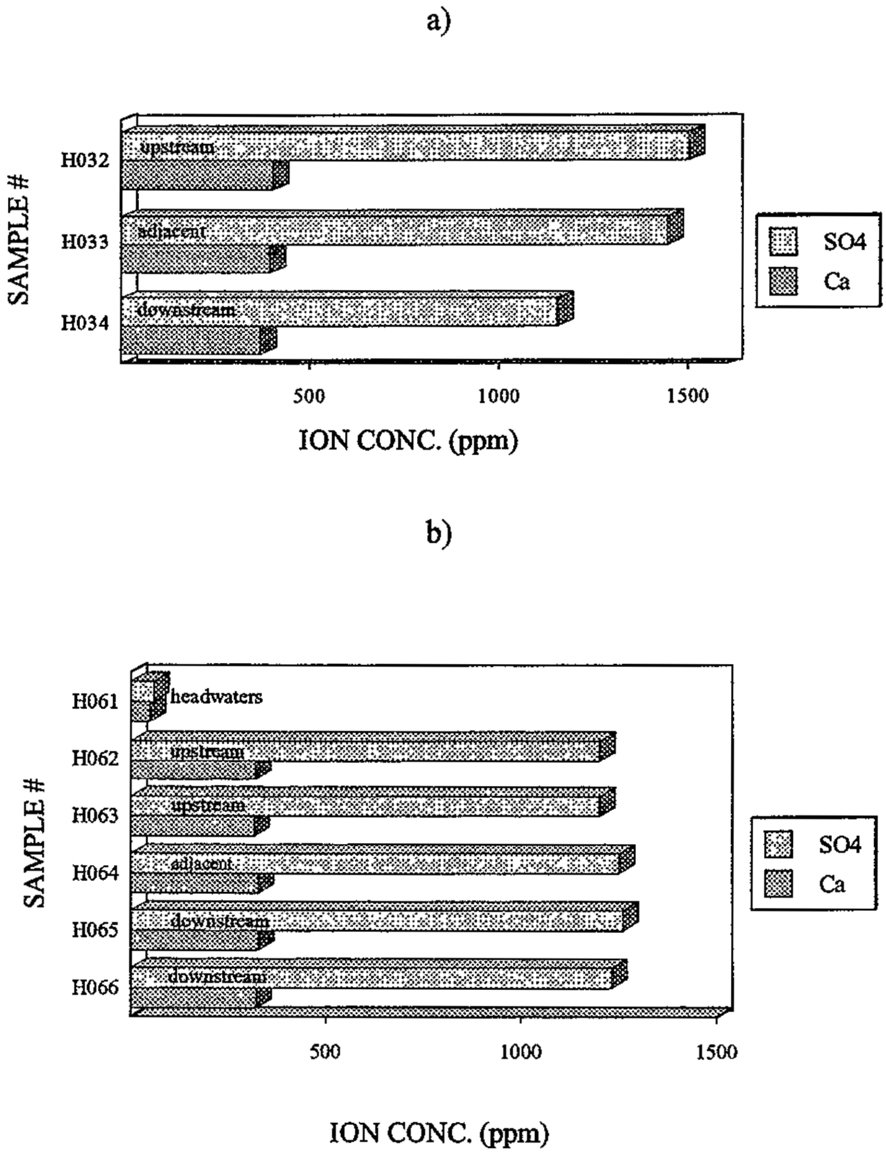


FIGURE 19. SO_4 and Ca ion concentrations in surface water samples from Hanover Creek: a) samples taken in August, b) samples taken in January.

The pH increases downstream, while total dissolved solids and hardness decrease (Table 11).

Table 11. pH, TDS, and hardness for surface water samples taken from Hanover Creek.

SAMPLE #	LOCATION	pH	TDS (ppm)	HARDNESS (ppm)
August				
H032	upstream	7.75	2,262	1,530
H033	adjacent	7.75	2,193	1,509
H034	downstream	7.85	1,855	1,306
January				
H061	headwaters	8.1	232	189
H062	upstream	7.85	1,817	1,272
H063	upstream	8.1	1,815	1,260
H064	adjacent	8.2	1,879	1,298
H065	downstream	7.7	1,888	1,298
H066	downstream	8.2	1,851	1,277

Total dissolved solids and hardness decrease with increased flow (Table 11, increased flow in January). Bicarbonate, calcium and sulfate ion concentrations decrease with increased flow. Zinc concentrations increase with increased flow. Copper and lead could not be detected when samples H032, H033, and H034 were analyzed because the graphite furnace needed to detect small quantities was not available. It was available when H061- H066 were analyzed, so concentrations of these metals were measurable; however, it is not possible to compare concentrations with increased flow. Iron and lead concentrations are within drinking water limits, although Hanover Creek is not a source of local water supply.

Bullfrog

Tailings

The Main, NW, and NE tailings piles were sampled at the surface to determine similarities and/or differences to the Hanover tailings. Samples BF001, BF002, BF007, and BF018 are similar in appearance to surface samples taken at the Hanover site. BF003 and BF030 were removed from the side of the Main tailings pile. BF003 represents oxidized (orange) material and BF030 is a white precipitate found along clay-rich horizons.

Lead concentrations in surface tailings are below 70 ppm and Zn concentrations range from 600 to 38,000 ppm (Table 12). Net acid-producing potentials are all negative (Fig. 20).

Table 12. Lead and zinc concentrations in surface tailings samples from Bullfrog tailings piles.

SAMPLE #	Pb (ppm)	Zn (ppm)
BF001	41	2,000
BF002	67	8,100
BF003 (oxidized)	4,400	2,100
BF007	45	600
BF018	54	3,500
BF030 (precipitate)	1,000	38,000

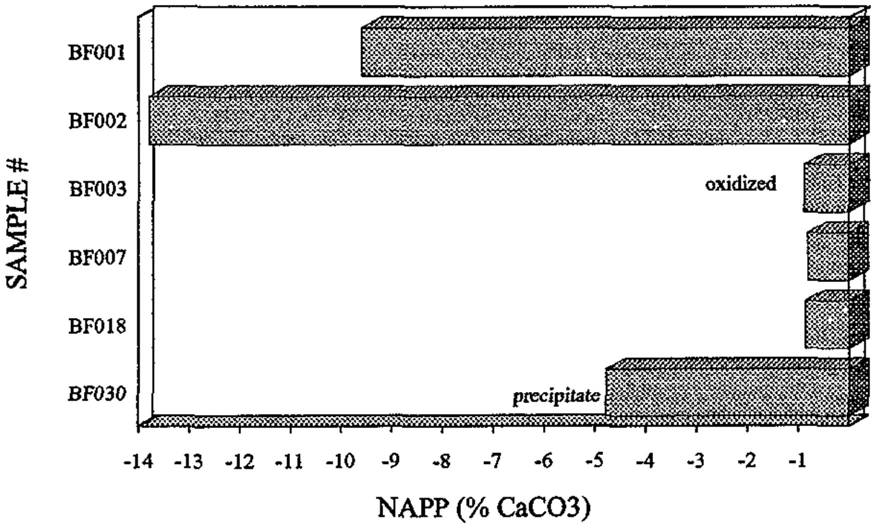


FIGURE 20. NAPP for surface tailings samples taken on the Main and NE tailings piles at the Bullfrog site.

Tailings Core

Underlying rock from 9 of the 11 holes drilled into the Bullfrog tailings piles was analyzed for Pb, Cu, Zn, and Cd concentrations. Core from BF II and BF VII did not reach underlying rock. Tailings material was analyzed from BF I and BF III only. In both cases, underlying rock contains much less Pb, Cu, and Zn than the tailings (Table 13).

Table 13. Lead, copper, and zinc concentrations in rocks underlying Bullfrog tailings.

SAMPLE #	HOLE #, DEPTH (m)	Pb (ppm)	Cu (ppm)	Zn (ppm)
BF031	BF I, 8.9-9.1	2,900	600	8,000
BF032	BF I, 9.1-9.1	370	40	780
BF033	BF III, 18.6-18.7	1,800	500	12,500
BF034	BF III, 18.7-18.9	370	75	1,400
BF035	BF IV, 15.2-15.7	1,900	315	990
BF036	BF IV, 15.7-16.7	3,100	205	3,700
BF037	BF V, 19.5-19.6	215	130	405
BF038	BF V, 19.6-19.8	50	60	160
BF039	BF VI, 25.1-25.8	605	65	2,100
BF040	BF VIII, 5.7-6.1	1,300	85	640
BF041	BF IX, 5.5-6.1	60	25	1,100
BF042	BF X, 14.9-15.1	85	50	980
BF043	BF X, 15.1-15.2	<40	80	300
BF044	BF XI, 8.5-9.1	50	30	200

Mineralogy for underlying rocks consists of quartz, feldspar, and clay minerals (principally illite, kaolinite, and smectite and/or I/S), with lesser amounts of dolomite in six samples (Appendices A and C). Acid-neutralizing potential, net acid producing potential, soil pH, and bulk mineralogy were also determined.

ANPs are positive and NAPPs are negative; this suggests an alkaline environment (Appendix B). Soil pH ranges from 7.4 to 8.2 with one exception of 5.5 for BF037 (Table 14). The two tailings samples have pH of 7.8 (BF033) and 7.9 (BF031).

Table 14. pH of core rocks and tailings.

SAMPLE #	pH	SAMPLE #	pH
BF031	7.9	BF039	7.4
BF032	8.2	BF040	7.7
BF033	7.8	BF041	8.1
BF034	7.9	BF042	8.1
BF035	8.2	BF043	8
BF036	8.2	BF044	8.1
BF037	5.5		
BF038	7.8		

Soils

Surface and subsurface soils were taken west of the NW tailings pile to ensure no contamination from the tailings. Lead concentrations range from 190 ppm at the surface to 110 ppm 5-10 cm at depth (Fig. 21). ANPs and NAPPs for these samples are in Table 15.

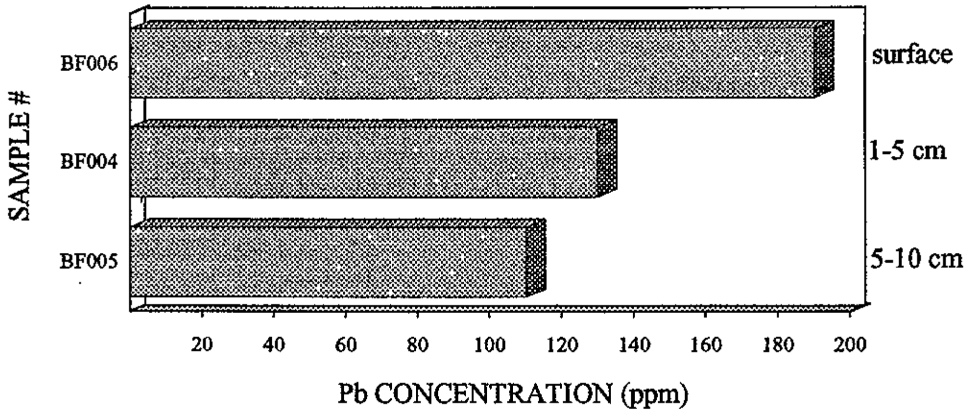


FIGURE 21. Lead concentrations in control soils taken west of the NW tailings pile.

Table 15. ANPs and NAPPs in control soils.

SAMPLE #	DEPTH (cm)	ANP (% $CaCO_3$)	NAPP (% $CaCO_3$)
BF006	0-1	5.9	-8.3
BF004	1-5	19.7	-19.1
BF005	5-10	6.4	-5.9

Samples taken from the pit north of the Main tailings pile on a mineralized bank show Pb concentrations elevated above those of the control samples. The range is from 290 ppm (15-20 cm below the surface) to 1000 ppm on the surface (Fig. 22a). Copper content for these samples decreases rapidly from 1200 ppm at the surface to 100 ppm 1-5 cm at depth (Fig. 22b). ANPs range from 4.1 to 13.4 (% $CaCO_3$) with the highest being 5-10 cm below the surface. The lowest NAPP also occurs at this depth (Table 16).

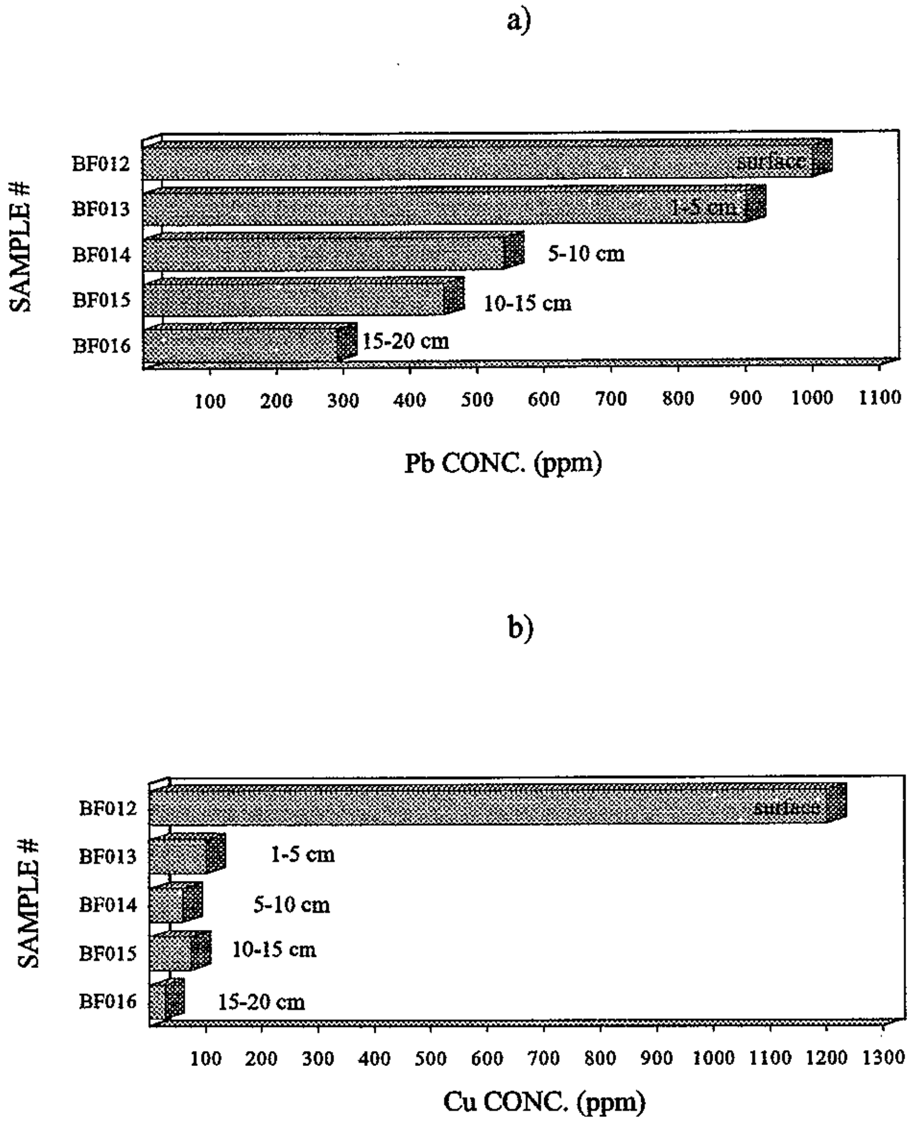


FIGURE 22. Soil profile northeast of the Main tailings pile at the Bullfrog site: a) Pb concentrations, b) Cu concentrations.

Table 16. ANPs and NAPPs for a soil profile northeast of the Main tailings pile.

SAMPLE #, DEPTH (cm)	ANP ($\%CaCO_3$)	NAPP ($\%CaCO_3$)
BF012, 0-1	10.9	-8.2
BF013, 1-5	5.2	-5.2
BF014, 5-10	13.4	-13.3
BF015, 10-15	4.1	-4.1
BF016, 15-20	6.8	-6.7

A third set of subsurface soils sampled northeast of the NW tailings pile contains lesser amounts of Pb than are found in the control area (Table 17). Copper and zinc concentrations are elevated above undisturbed levels; copper concentrations decrease with increasing depth while zinc concentrations initially decrease and then increase with increasing depth (Fig. 23).

Table 17. Pb concentrations in control samples and in subsurface soils northeast of the NW tailings pile.

SAMPLE #, DEPTH (cm)	Pb (ppm)	SAMPLE #, DEPTH (cm)	Pb (ppm)
control		**northeast**	
BF006, 0-1	190	BF020, 0-1	42
BF004, 1-5	130	BF021, 1-10	34
BF005, 5-10	110	BF022, 10-15	40
		BF023, 15-20	40
		BF024, 20-25	45

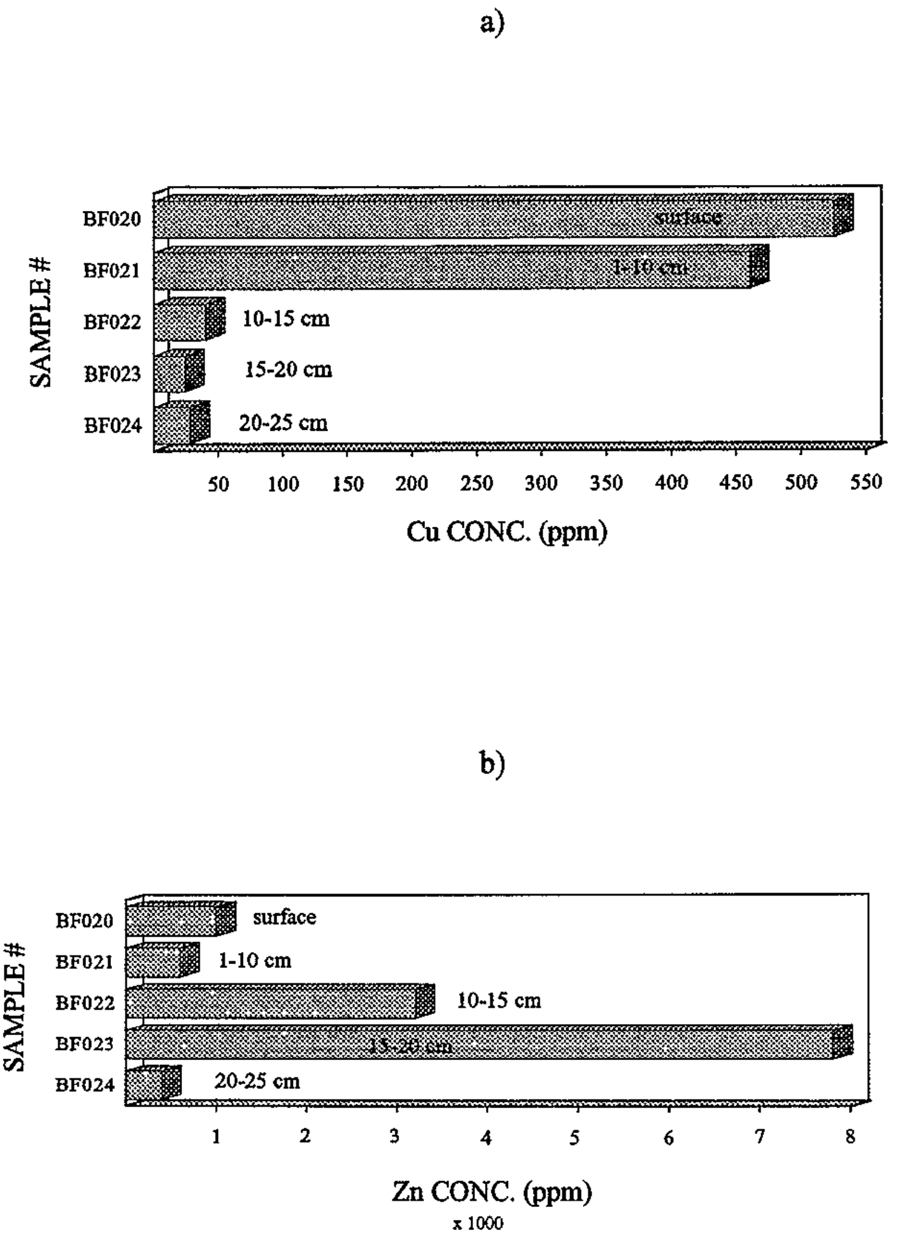


FIGURE 23. Soil profile taken northeast of the NW tailings pile: a) Cu concentrations and b) Zn concentrations.

Plants

Plant foliar samples were taken near the control soils, in a wind-blown area northeast of the NW tailings pile, on the north edge of the NW tailings pile, and northeast of the Main tailings pile in an area of wind-blown tailings deposition (Fig. 24). Plant varieties sampled include; prickly pear and cholla cacti, and a young juniper tree (Fig. 3).

Lead concentrations vary from 0.57 to 6.3 ppm with one of the control samples actually containing more lead than one growing on the edge of the Main tailings (Table 18). The toxicity level of Pb in plants is 30-300 ppm (Fergusson, 1990). A plot of soil Pb and plant Pb is shown in Fig. 25. Cadmium toxicity to plants occurs between 5-30 ppm. Concentrations of Cd range from 0.04 ppm (BF008) to 4.4 ppm (BF011; Appendix A).

FIGURE 24. Vegetation north of the NW pile is being engulfed by wind-blown tailings.

Table 18. Lead concentrations in plants taken near the tailings at the Bullfrog site.

SAMPLE #	DESCRIPTION	LOCATION	Pb (ppm)
BF008	prickly pear cactus	west of NW tailings	0.6
BF009	cholla cactus	same	4.6
BF010	prickly pear cactus	edge of NW	5.8
BF011	young juniper	north of NW	6.3
BF017	prickly pear cactus	northeast of Main	0.6

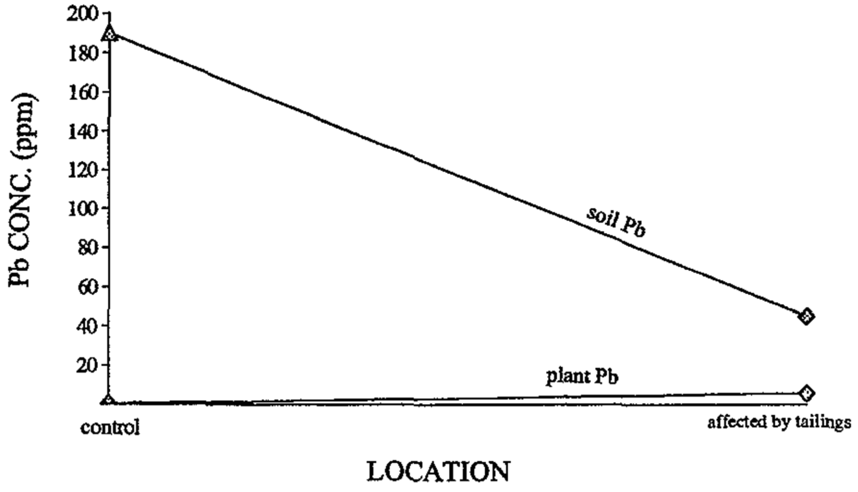


FIGURE 25. Lead concentrations in 2 soils and 2 plants ("control" is west of NW tailings pile and "affected by tailings" is in the wind-blown area on the edge of the NW tailings).

Surface Water

Evidence of water drainage from the Main tailings pile toward Whitewater Creek is seen after times of heavy rainfall (Fig. 3). A pool of water was found on a secondary tier of the pile after such a rainstorm. Water analyzed from the pool showed a pH of 2.75, hardness of 20,058 ppm, Pb concentration of 1.8 ppm, Cu concentration of 17 ppm, Zn concentration of 5,300 ppm, and Fe concentration of 590 ppm (Appendix A).

DISCUSSION

Tailings

The tailings piles at the Hanover and Bullfrog sites are relatively stable, both mechanically and geochemically. Silicate minerals (i.e. garnet and quartz) account for approximately 80% of the material present (Walder, unpubl. report for MRRC, 1992). Garnet and quartz are known for their ability to withstand chemical weathering. Sulfides present are usually rimmed with an insoluble oxide protecting them from oxidation and interaction with water so they are incapable of producing acid (Walder, unpubl. report for MRRC, 1992). The surface oxidation of sulfides on the Main tailings pile at the Bullfrog site could be minimized by capping the pile, first with a clay layer and then a layer of top soil.

The tailings have an alkaline nature as evidenced by negative net acid-producing potentials and pHs above 7.0. The semi-arid climate found in the Southwest enhances this alkalinity because there is not an abundance of water in contact with the piles. However, the presence of a stream on or near the tailings would increase the probability of acid generation within the them. Such is the case at the Cleveland Mill site in the same area as the Hanover and Bullfrog sites.

The Cleveland.Mill site is located north of Silver City, New Mexico. Waste material at the Cleveland Mill is roughly the same composition as the material found in the tailings at Hanover and Bullfrog (McLaughlin, 1989). Material is transported from the site by a stream and deposited in a nearby creek. Sulfuric acid is produced in the process even though the Mill site is in the same semi-arid climate as the Hanover and Bullfrog sites because of the presence of this stream (McLaughlin, 1989).

Waste material from the Pb-Zn tailings pond (in Alamitos Canyon) studied by Sidle et al. (1991) in northern New Mexico is also transported off-site by a nearby stream with a pH of 6.0. Metals are being transported in solids rather than in aqueous solution. Fluvial processes are at least as important as chemical processes in controlling the distribution of metals at the site (Sidle et al., 1991). Annual precipitation is only slightly more in this area than in southwestern New Mexico. This shows that climate is not the only element working to stabilize the Hanover and Bullfrog sites.

Calcite is present in large quantities in all the tailings piles at the Hanover and Bullfrog sites. Material at both sites is derived from skarn deposits which contain calcite. At the Hanover site, the tailings contain more calcite because of liming (a process used during ore recovery). The presence of calcite increases the acid neutralizing potential in the tailings material. The abandoned Pb-Zn mine in the United Kingdom(Johnson and Eaton, 1980) does not contain an abundance of calcite. This, combined with the humid climate and nearby stream, allows for the production of acid upon interaction with waste material.

Surrounding Soils

Windblown tailings material contains relatively low amounts of Pb, Cu, Zn, and Cd. As a result, the soils surrounding the Hanover and Bullfrog tailings piles contain relatively low amounts of these elements. The heavy metals that are present are contained primarily in the upper 20 cm of soil. The alkaline nature of the soils (evidenced by negative NAPPs) prevents the downward transport of heavy metals.

Alkaline soils are not found throughout the United States. For instance, soils in southern and eastern United States are more acidic because of the humid climate. As a result, acid mine drainage is of more concern in mines in these areas. The Tar Creek area of Oklahoma is one example (Keller, 1988). Many studies of acid mine drainage have been conducted near coal mines in the east (Brady, et al., 1986; Singer and Stumm, 1970). It is important to note that the nature of the soils as well as the difference in climate in these areas makes the problem of reclamation a difficult one to solve.

Vegetation Near the Tailings

Concentrations in plants growing near the Hanover and Bullfrog tailings piles confirm the low concentrations of heavy metals in the soils. None of the plants sampled contain heavy metals in large enough quantities to be adversely affected. Other studies (Sidle et al., 1991; Austin et al., 1993b) in New Mexico showed similar results.

Interaction with Surface Water

Tailings material deposited along Hanover Creek creates a point of interaction between the creek and tailings. However, water sampled shows no adverse affects from this interaction as seen by insignificant decreases in Pb content and SO_4 ion content downstream. This is most likely due to the presence of calcite in the tailings. The calcite provides Ca^{2+} ions that combine with SO_4 ions in the water to form gypsum. The increase in pH downstream of the tailings material may explain the observed decrease in Pb concentration.

Groundwater Contamination

Groundwater in Grant County is generally 200 ft below the surface with the exception of some shallow perched water tables. A a result, the threat of contamination is minimal in this area. This is true for the Cleveland Mill site as well (Site Investigation, New Mexico Environment Department, 1993).

CONCLUSIONS

Major dissolved ion transportation pathways such as fluvial and/or eolian transport of solids, and plant uptake of heavy metals have been examined for the Hanover and Bullfrog tailings sites to determine the effects of the tailings on the surrounding environment. Surface soils, subsurface soils, plants, and surface waters were sampled.

The Hanover tailings pile is relatively stable both mechanically and geochemically. Surrounding soils and vegetation contain relatively low amounts of heavy metals. Water analyzed from Hanover Creek shows no adverse affects from interaction with the tailings deposited along the creek. The groundwater table is about 200 ft below the surface in the vicinity of the tailings piles so the possibility of contamination is minimal.

The Main tailings pile at the Bullfrog site shows visible evidence of oxidation at the surface. Fluvial transport of tailings occurs during/after summer thunderstorms. However, this and the oxidation are surface phenomenon and may be drastically reduced with the emplacement of a protective cover over the Main tailings. Soils and vegetation surrounding the tailings contain relatively low amounts of heavy metals except for soils on mineralized areas.

In contrast, rocks underlying the Hanover tailings contain less Pb than those underlying the Bullfrog tailings. This reflects different ore recovery capabilities at the two sites as well as the mineralization under the Main tailings pile at Bullfrog. NAPPs are negative for underlying rock material at both sites.

Covering both piles with topsoil and revegetating would eliminate eolian and fluvial transport of metal-bearing particles as well as oxidation of surface materials due to exposure. Removal of the tailings such as may be suggested by the EPA may cause more harm than leaving them in place. Such an action would probably release metal-containing-inhalable dust in the air.

FURTHER WORK

A comprehensive study of the groundwater is needed. Trauger (1972) compiled a thorough account of water resources and general geology for Grant County with data from the 1950s to 1974. However, additional mining and pumping have undoubtedly changed the contours of the water table in the past 20 years. Depth to the water table is important when assessing the risk of contamination due to heavy metals downward movement and should be accurately known. Blood testing may need to be performed on people living in the vicinity of the Bullfrog site (in the townsite of Vanadium) to measure exposure.

Revegetation is one option for reclamation of the two sites; others may need to be explored more fully. For instance, it has been suggested that garnet found in the Hanover tailings could be used as an abrasive. Options such as this would make use of the tailings. In a time when mining is being restricted, it is far better to identify and utilize such resources as garnet found in Hanover tailings rather than discard them as waste material.

REFERENCES

Austin, G. S., Brandvold, L. A., and Stone, W. J., 1990, Lead contamination of soil near the abandoned Billing Smelter, Socorro, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Open File-Report T-90-2, 27 p.

Austin, G. S., Brandvold, L. A., Hawley, J. W. , and Renault, J., 1993a, Lead contamination at an old smelter site Socorro, New Mexico: Part I-Particle size and depth of contamination: Mining Engineering, v. 25.

Austin, G. S., Brandvold, and Renault, J., 1993b, Lead contamination at an old smelter site at Socorro, New Mexico: Part II-Laboratory tests: Mining Engineering, v. 25.

Brady, K. S., Bigham, J. M., Jaynes, W. F., and Logan, T. J., 1986, Influence of sulfate on Fe-oxide formation; comparisons with a stream receiving acid mine drainage: Clays and Clay Minerals, v. 34, p. 266-274.

Brickell, T. G., 1991, Characterization of lead contamination near the Graphic Smelter ("Cuba Road" Smelter), Socorro, New Mexico, abstract: New Mexico Geology, v. 13, p. 92.

Chambers, J. C., and Sidle, R. C., 1991, Fate of heavy metals in an abandoned lead-zinc tailings pond: I. Vegetation: Journal of Environmental Quality, v. 20, p. 745-751.

Chaney, R. L., 1988, Metal speciation and interaction among elements affect trace element transfers in agricultural and environmental food-chains, in Kramer, J. R., and Allen, H. E., eds., Metal speciation: Theory, Analysis and Application, p. 219-260.

Chaney, R. L., Mielke, H. W., and Sterrett, S. B. , 1989, Speciation, mobility, and bioavailability of soil lead; in Proceedings of the International Conference on Lead in Soils: Issues and Guidelines, Environmental Geochemical Health (Supplement), p. 105-129.

Davis, A., Ruby, M. V., and Bergstrom, P. D. , 1992, Bioavailability of arsenic and lead in soils from the Butte, Montana Mining District: Environmental Science and Technology, v. 26, p. 461-468.

Elliott, H. A., Liberati, M. R., and Huang, C. P., 1986, Competitive adsorption of heavy metals by soils: Journal of Environmental Quality v. 15, p. 214-219.

Fergusson, J. E., 1990, The Heavy Elements: Chemistry, Environmental Impact and Health Effects: New York, Pergamon Press, 614 p.

Fergusson, J. E., 1986, Lead: Petrol lead in the environment and its contribution to human blood lead levels: The Science of the Total Environment, v. 50, p. 1-54.

Johnson, M. S., and Eaton, J. W., 1980, Environmental contamination through residual trace metal dispersal from a derelict lead-zinc mine: Journal of Environmental Quality, v. 9, p. 175-179.

Jones, W. R., and Hernon, R. M., 1973, Ore deposits and rock alteration of the Santa Rita quadrangle, Grant County, New Mexico: U. S. Geological Survey, Professional Bulletin 214 371, 102 p.

Jones, W. R., Hernon, R. M., and Moore, S. L., 1967, General geology of Santa Rita quadrangle, Grant County, New Mexico: U. S. Geol. Survey Professional Paper 555, 144 p.

Keller, E. A., 1988, Environmental Geology, Columbus, Merrill Publishing Company, 540 p.

Kloke, A., Sauerbeck, D. R., and Vetter, H., 1984, The contamination of plants and soils with heavy metals and the transport of metals in terrestrial food chains; in Nriagu, J. O., ed., Changing Metal Cycles and Human Health, Dahlem Konferezen, p. 113-141.

Levy, D. B., Barbarick, K. A., Siemer, E. G., and Sommers, L. E., 1992, Distribution and partitioning of trace metals in contaminated soils near Leadville, Colorado: Journal of Environmental Quality, v. 21, p. 185-195.

McLaughlin, J., 1989, Site Assessment of Cleveland Mill Site, Grant County, New Mexico: Ecology and Environment, Inc., 30p.

Neuman, D. R., and Dollhopf, D. J., 1992, Lead levels in blood from cattle residing near a lead smelter: Journal of Environmental Quality, v. 21, p. 181-184.

Needleman, H. L., ed., 1990, Case Studies in Environmental Medicine: Lead Toxicity: U. S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry: pamphlet, 27 p.

Sidle, R. C., . Chambers, J. C, and Amacher, M. C., 1991, Fate of heavy metals in an abandoned lead-zinc tailings pond: II. Sediment: Journal of Environmental Quality, v. 20, p. 752-758.

Singer, P. C., and Stumm, W., 1970, Acid mine drainage: The rate determining step: Science, v. 167, p. 1121-1123.

Smith, R. M., Grube, W. E. Jr., Arkle, T. Jr., and Sabek, A., Mine spoil potentials for soil and water quality: U. S. Environmental Protection Agency, Cincinnati, Ohio Professional Bulletin 237 525, 75 p.

Thornton, I., Culbard, E., Moorcroft, S., Watt, J., Wheatley, M., and Thompson, M., 1985, Metals in urban dusts and soils: Environmental Technology, Letter 6, p. 137-144.

Trauger, F. D., 1972, Water resources and general geology of Grant County, New Mexico: New Mexico Bureau of Mines and Mineral Resources, Hydrologic Report 2, 211 p.

Tyler, L. D., and McBride, M. B., 1982, Mobility and extractability of Cd, Cu, Ni, and Zn in organic and mineral soil columns: Soil Science, v. 134, p. 198-205.

Wilson, L., 1981, Potential for groundwater polluton in New Mexico: New Mexico Geological Society, Special Publication 10, p. 47-54.

APPENDIX A
Chemical Data

HANOVER SOILS AND TAILINGS

sample#	Cu (ppm)	Pb (ppm)	Zn (ppm)	Bi (ppm)	Cd (ppm)	Co (ppm)	%PyS	ANP(%CaCO3)	APP(%CaCO3)	NAPP (APP-ANP)	NAPP (EPA)
H001A	1050	660	5700	50	1.2	15	1.39	19.9	2.81	-15.5	-17.7
H001B	780	330	2900	54	8.4	40	2.4	14.9	1.75	-13.15	-13.2
H002	199	315	4100	57	12	85	1.02	22.9	5.03	-17.87	-18
H003	820	320	2500	45	1	1.9	1.32	13.4	1.52	-9.28	-11.9
H004	1100	124	1200	35	3.9	78	0.92	12.6	2.13	-10.47	-10.5
H005	1400	840	6400	36	16	67	2.69	11.3	2.15	-9.15	-9.2
H007	255	270	3200	35	8	67	1.03	11.52	2.95	-8.55	-8.6
H008	300	300	8300	37	19	73	2.13	10	2.34	-7.66	-7.7
H009	610	170	3500	34	9	74	1.5	9.8	1.48	-8.32	-8.3
H012	435	170	3900	939	9.8	86	1.69	9.1	3.17	-5.93	-5.9
H013	425	300	4300	37	12	76	1.33	8.3	2.94	-5.36	-5.4
H018	350	740	9800	54	26	120	X	0	1.32	1.32	1.3
H019	200	870	14400	42	41.2	100	X	7.7	1.1	-6.6	-7.6
H029	97	100	1300	25	4.9	52	X	4.8	6.5	1.7	-4.2
H015	97	49	11300	<24	2.9	45	X	11.6	1.7	-9.9	-11.4
H016	110	60	11000	<24	4	38	X	10	2.3	-7.7	-9.8
H017	100	130	8400	24	5.9	52	X	11.1	1.3	-9.8	-11
H015dup	66	40	7700	<24	2.9	35	X	X	X	;X	X
H022	340	3500	4400	54	11.7	120	X	11.6	2.69	-8.91	-8.9
H023	160	430	5700	45	14.4	88	X	9.3	1.32	-7.98	-8
H024	95	600	7500	32	14.3	66	X	9.3	1.3	-8	-9.2
H025	110	570	6100	50	9.4	120	X	8.9	0.63	-8.27	-8.8
H026	23	1400	3300	42	24.4	73	X	7.5	0	-7.5	-7.5

x = analysis not done

HANOVER TAILINGS CORE: CHEMICAL ANALYSES

Sample #	Pb (ppm)	Cu (ppm)	Cd (ppm)	Zn (ppm)	% FeS2	%SO4,S	Total S%	ANP(%CaCO3)	APP (%CaCO3)	NAPP(EPA)	soil pH	HOLE #	Depth (m)	Description
H035	440	240	20	4000	5.6	0.03	2	12.7	6.2	-6.5	7.5	H1	24.0-24.3	t
H036	530	230	20	4000	6.6	0.04	2.5	15.8	7.8	-8	7.7	H1	24.3-24.6	t
H037	750	340	26	6000	9.9	0.04	3.1	13.4	9.6	-3.8	7.4	H1	24.6-24.9	t
H038	670	290	28	5200	7.9	0.08	2.88	14.3	8.8	-5.5	8.1	H1	24.9-25.2	t
H039	750	220	32	7200	10.6	0.03	3.5	16.8	10.8	-6	7.7	H1	25.2-25.5	t
H040	700	280	30	5600	6.9	0.06	4.16	15.6	12.8	-3	7.8	H1	25.5-25.8	t
H041	690	330	24	5000	6	0.06	2.7	19.3	8.3	-11	7.3	H1	25.8-26.1	t
H042	690	330	22	5600	7.8	0.05	2.9	15.2	8.9	-6.3	7.4	H1	26.1-26.4	t
H043	92	150	<20	940	2.5	0.01	0.3	2	0.9	-1.1	7.6	H1	26.4-27.0	rock
H047	790	1170	58	19900	4.2	1.04	2.6	30.2	4.9	-25.5	7.9	H2	33.0-33.6	t
H048	1700	5200	<20	7100	0.62	0.16	0.64	27	1.5	-25.5	8.4	H2	33.6-33.8	t
H056	396	102	<20	5100	0.37	0.01	<0.1	4.6	x	-4.6	9	H2	33.8-34.2	rock
H057	382	165	<20	5300	0.35	0.12	0.24	6.6	0.4	-6.4	8.6	H2	34.2-34.5	rock
H049	1500	900	26	9900	3.23	0.09	1.7	27.6	5.03	-22.6	7.8	H3	15.1(2.5c	clay
H050	480	390	32	11900	3.79	0.04	2.7	17.9	7.4	-10.5	7.6	H3	16.8-17.1	t
H051	8700	300	20	6900	3.03	0.05	2.1	18.1	6.4	-11.7	7.7	H3	17.1-17.3	t
H052	393	60	<20	2300	0.55	0.05	0.67	5.8	1.94	-3.86	7.7	H3	17.3-17.4	rock
H053	174	58	<20	1600	0.2	0.03	0.2	6.1	0.63	-5.47	7.8	H4	18.0-18.6	rock
H054	81	40	<20	1000	0.29	0.03	<0.1	8.4	x	-8.4	7.7	H4	18.6-19.2	rock
H055	48	50	<20	570	0.23	0.02	0.64	6.5	1.94	-4.56	7.5	H4	19.2-19.5	rock
H058	1400	670	<20	4900	9.97	0.1	2.63	25.4	7.81	-17.6	7.8	H6	21.0-21.2	t
H059	60	73	<20	224	0.49	0.02	<<0.1	10.9	x	-10.9	8.2	H6	22.2-22.8	rock
H060	42	58	<20	180	0.19	0.01	<1.0	15.2	x	-15.2	8.2	H6	22.8-24.0	rock

t = tailings material
rock = underlying rock material
x = analysis not done

BULLFROG SOILS AND TAILINGS

Sample #	Pb (ppm)	Cu (ppm)	Zn (ppm)	Bi (ppm)	Cd (ppm)	Co (ppm)	%Py S	%total S	Total Fe	ANP (%CaCO3)	APP (%CaCO3)	NAPP (APP-ANP)	NAPP (EPA)
BF001	41	820	2000	48	1.5	35	1.0	1.16	x	10.9	1.3	-9.6	-9.6
BF002	67	780	8100	63	13.5	131	0.76	1.2	x	15.9	2.09	-13.81	-13.8
BF007	45	620	600	67	4.2	69	1.1	1.1	x	9.3	1.03	-8.27	-0.82
BF018	54	480	3500	35	8.1	89	1.23	1.3	x	7.9	1.2	-6.7	-0.67
BF003	4400	300	2100	39	<1.0	<5.0	0.83	5.4	x	2.09	1.2	-0.89	-0.89
BF030	1000	225	38000	27	166	40	0.85	4.73	2.7	8.0	3.24	-4.76	-4.8
BF019	41	640	1500	35	3.8	118	0.79	0.79	11.1	8.5	1.24	-7.26	-7.3
BF025	220	340	900	26	2.9	77	0.45	0.45	7	6.3	1.02	-5.28	-5.3
BF026	170	250	1100	25	3.3	83	0.56	0.56	8.9	6.7	1.15	-5.55	-5.6
BF027	320	370	2100	26	4.9	108	0.76	0.76	10.0	7.0	1.67	-5.33	-5.3
BF005	110	20	540	n/s	1.0	<5.0	0.09	<42ppm	x	6.4	0.0	-6.4	-5.9
BF004	130	73	4900	15	<1.0	<5.0	0.08	<17ppm	x	19.7	0.62	-19.08	-19.1
BF006	190	90	730	n/s	<1.0	<5.0	0.11	<83ppm	x	5.9	0.0	-5.9	-8.3
BF016	290	27	1100	18	<1.0	<5.0	0.07	0.03	x	6.8	0.12	-6.68	-6.7
BF015	450	73	2100	24	<1.0	<5.0	0.07	0.07	x	4.1	0.0	-4.1	-4.1
BF014	540	58	3000	25	<1.0	<5.0	0.1	0.11	x	13.4	0.115	-13.285	-13.3
BF013	900	100	2800	23	<1.0	<5.0	0.09	0.14	x	5.2	0.0	-5.2	-5.2
BF012	1000	1200	6000	36	<1.0	17	1.1	1.3	x	10.9	2.74	-8.16	-8.2
BF020	42	525	1000	42	3.6	127	1.03	1.03	14.3	7.2	1.57	-5.63	-5.6
BF021	34	460	600	34	3.1	115	0.02	0.42	x	7.6	0.85	-6.75	-6.8
BF022	40	40	3200	14	<1.0	25	0.07	0.14	2.2	6.7	0.0	-6.7	-6.7
BF023	40	24	7600	14	<1.0	24	0.05	0.09	2.1	7.8	0.0	-7.8	-7.8
BF024	45	28	400	15	1.9	30	0.05	0.15	1.7	7.6	0.0	-7.6	-7.6

x = analysis not done
n/s = no sample

BULLFROG TAILINGS CORE: CHEMICAL ANALYSES

Sample #	Pb (ppm)	Cu (ppm)	Cd (ppm)	Zn (ppm)	% FeS2	%SO4,S	Total S%	ANP(%CaCO3)	APP (%CaCO3)	NAPP(EPA)	soil pH	HOLE #	Depth (m)	Description
BF031	2900	600	20	8000	4.2	0.16	2.6	27.3	8.1	-19.2	7.9	I	8.7-8.9	t,clay-rich
BF032	370	40	<20	780	0.28	0.03	0.53	4	1.66	-2.34	8.2	I	8.9-9.0	rock
BF033	1600	500	30	12500	3.22	0.07	2	18.1	6.25	-11.85	7.8	III	18.3-18.4	t
BF034	370	75	<20	1400	0.28	0.003	<0.1	5	x	-5	7.9	III	18.4-18.6	rock
BF035	1900	315	<20	990	0.64	0.5	1.1	4.3	3.44	-0.86	8.2	IV	15.0-15.4	rock
BF036	3100	205	<20	3700	0.25	0.03	0.22	6.5	0.69	-5.81	8.2	IV	15.4-16.5	rock
BF037	215	130	<20	405	0.24	0.04	0.45	9.3	1.41	-7.89	5.5	V	19.2-19.3	rock
BF038	50	60	<20	160	0.26	0.01	<0.1	9.6	x	-9.6	7.8	V	19.3-19.5	rock
BF039	605	65	<20	2100	0.2	0.04	0.23	5.2	0.72	-4.48	7.4	VI	24.7-25.4	rock
BF040	1300	85	<20	640	0.2	0.023	0.23	5.2	0.72	-4.48	7.7	VIII	5.6-6.0	rock
BF041	60	25	<20	1100	0.26	0.01	0.2	6.8	0.63	-6.17	8.1	IX	5.4-6.0	rock
BF042	65	50	<20	980	0.61	0.03	0.7	6.1	2.19	-3.91	8.1	X	14.6-14.9	rock
BF043	<40	80	<20	300	0.18	0.004	0.17	6.1	0.53	-5.57	8	X	14.9-15.0	rock
BF044	50	30	<20	200	0.22	0.009	0.24	8.4	0.75	-7.65	8.1	XI	7.8-9.0	rock

t = tailings material
rock = underlying rock material
x = analysis not done

PLANT ANALYSES

SAMPLE#	%ASH	Co (ppm)	Cd (ppm)	Pb (ppm)	Cu (ppm)	Zn (ppm)	Description	Location
BF008	6.2	1.6	0.04	0.57	1.92	12.8	prickly pear	west of NW tailings(*)
BF009	3.27	1	0.27	4.6	7.8	59	cholla	west of NW tailings (*)
BF010	4.47	1.6	0.45	5.8	13	107	prickly pear	edge of NW (**)
BF011	5.27	1.8	4.4	6.3	23	116	young juniper	arroyo, north of NW (**)
BF017	6.8	1.6	0.12	0.6	1.72	33.3	prickly pear	northeast of Main (**)
H010	24.4	1.3	0.15	1.98	6.1	48.9	grass	northeast of tailings (**)
H020	2.6	1.7	0.05	0.7	1.2	14.4	cholla	arroyo, north of tailings (**)
H021	55.6	2.1	0.25	5.95	6.98	117.1	grass	same (**)
H027	3	1.3	0.04	0.7	1	13.4	cholla	Bull Hill (*)
H028	4.7	1.5	0.08	0.5	0.6	0.2	prickly pear	same (*)
H030	3.9	1	0.03	0.37	5.52	14.6	pinon	same (*)
H031	4.3	1	0.04	0.33	4.1	5.2	pine	same (*)

* = control sample
** = windblown area
H = Hanover site
BF = Bullfrog site

WATER ANALYSES

SAMPLE #	SITE	LOCATION	pH	TDS (ppm)	HARDNS(ppm)	CO3 (ppm)	HCO3(ppm)	Cl (ppm)	SO4 (ppm)	NO3 (ppm)
BF028	*Bullfrog*	pipe	7.1	2622	1087	0.0	170	20	910	0.7
BF029	*Bullfrog*	tailings	2.75	66024	20058	0.0	0	16	35750	0.3
H014	*Hanover Creek,M*	adjacent(**)	7.5	3511	1443	0.0	150	35	1310	0.2
H034	*Hanover Creek,A*	downstream(***)	7.85	1855	1306	0.0	233	45	1153	3.2
H033	*Hanover Creek,A*	adjacent(**)	7.75	2193	1509	0.0	200	44	1444	0.3
H032	*Hanover Creek,A*	upstream(*)	7.75	2262	1530	0.0	207	46	1500	0.3
H066	*Hanover Creek,J*	downstream(***)	8.2	1851	1277	0.0	190	23	1230	1.9
H065	*Hanover Creek,J*	downstream	7.7	1868	1298	0.0	190	23	1260	2.1
H064	*Hanover Creek,J*	adjacent(**)	8.2	1879	1298	0.0	192	23	1250	2.2
H063	*Hanover Creek,J*	upstream	8.1	1815	1260	0.0	196	23	1200	2
H062	*Hanover Creek,J*	upstream(*)	7.85	1817	1272	0.0	194	23	1200	1.8
H061	*Hanover Creek,J*	headwater	8.1	232	189	0.0	178	6.7	57	0.4

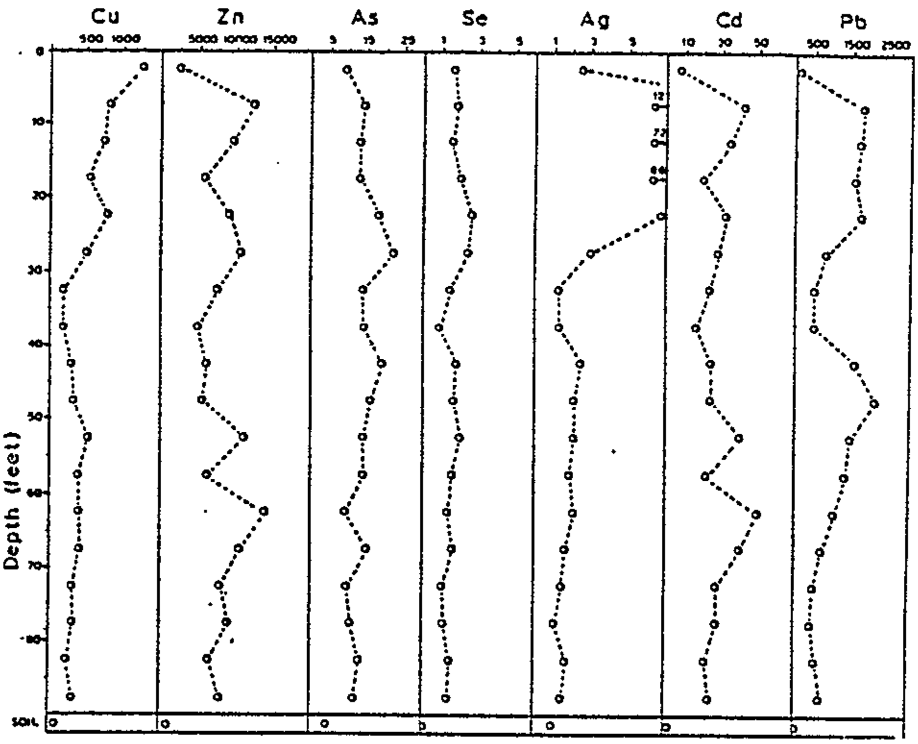
SAMPLE #	SITE	Cu (ppm)	Fe (ppm)	Pb (ppm)	Zn (ppm)	SIO2 (ppm)	Ca (ppm)	Na (ppm)	Mg (ppm)	K (ppm)
BF028	*Bullfrog*	<0.1	<0.30	<0.20	0.44	<20	320	40	70	3
BF029	*Bullfrog*	47	590	1.8	5300	90	580	80	4520	7
H014	*Hanover Creek*	<0.1	<0.3	<0.2	0.05	20	380	68	120	4
H034	*Hanover Creek*	0.03	<0.03	<0.05	0.9	21.4	368	68	94	7
H033	*Hanover Creek*	<0.02	<0.03	<0.05	<0.04	23.5	393	75	128	7.2
H032	*Hanover Creek*	<0.02	<.03	<.05	0.09	27.8	400	75	129	7.2
H066	*Hanover Creek*	50ppb	<100ppb	2ppb	0.46	x	320	60	116	4.9
H065	*Hanover Creek*	75ppb	<100ppb	1ppb	0.56	x	325	60	118	4.9
H064	*Hanover Creek*	0.37	0.39	3ppb	0.45	x	325	60	118	4.9
H063	*Hanover Creek*	75ppb	0.13	2ppb	0.33	x	315	57	115	4.9
H062	*Hanover Creek*	150ppb	<100ppb	1ppb	0.28	x	318	57	116	4.5
H061	*Hanover Creek*	7ppb	1.1	1ppb	0.03	x	47.7	12.8	17	1.4

x = analysis not done
M = sample taken in May
A = sample taken in August
J = sample taken in January

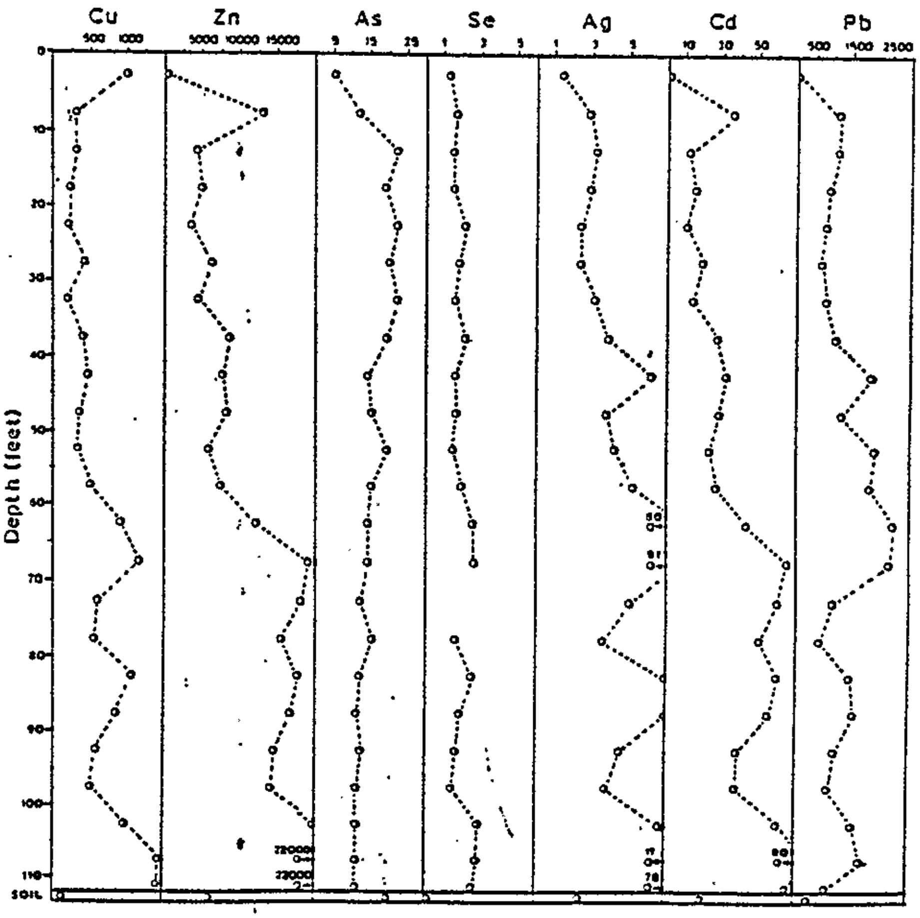
* = upstream samples taken at same location
** = adjacent samples taken in same location
*** = downstream samples taken in same location
HARDNS = hardness

APPENDIX B
Drill Core Data

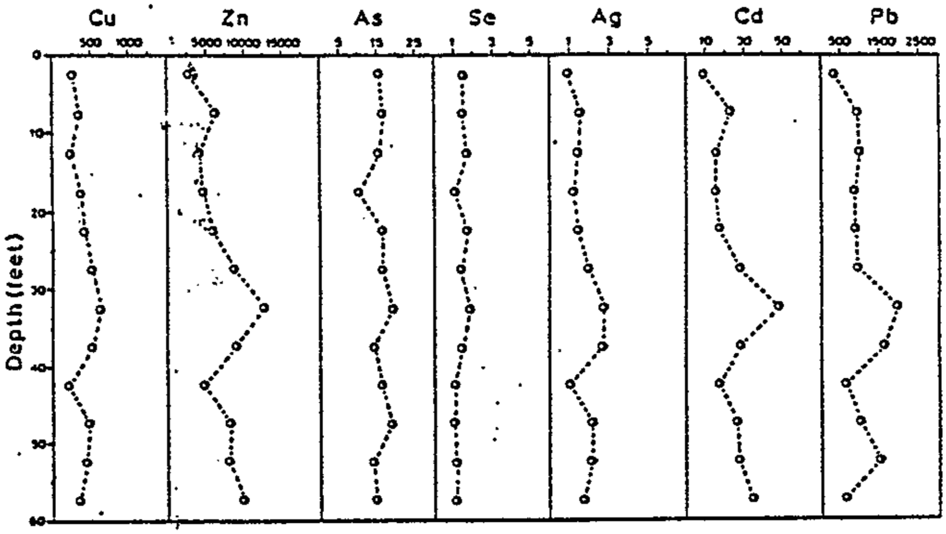
HOLE H1



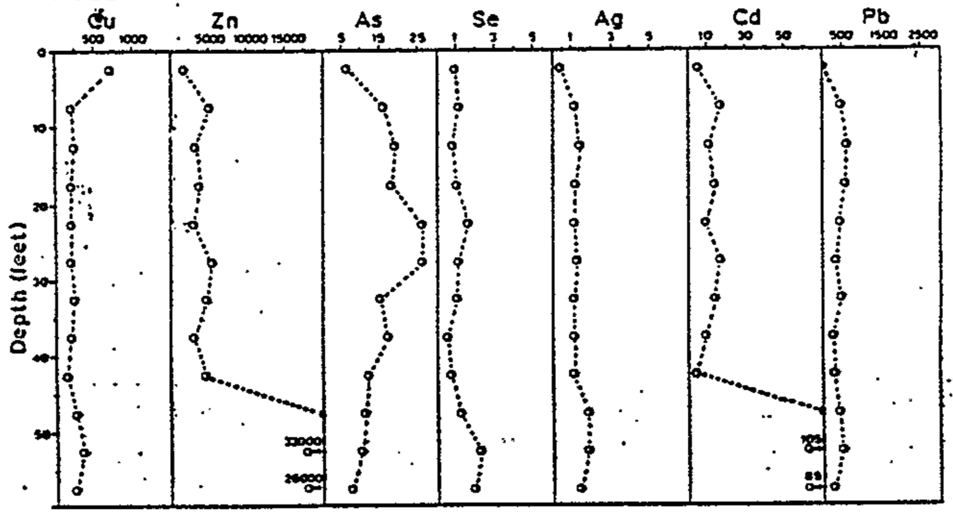
HOLE H2



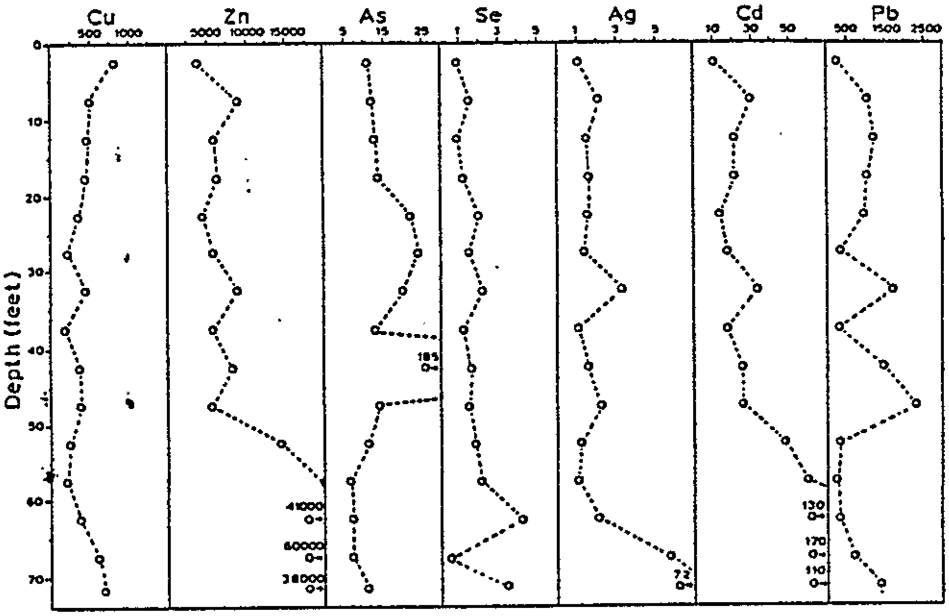
HOLE H3



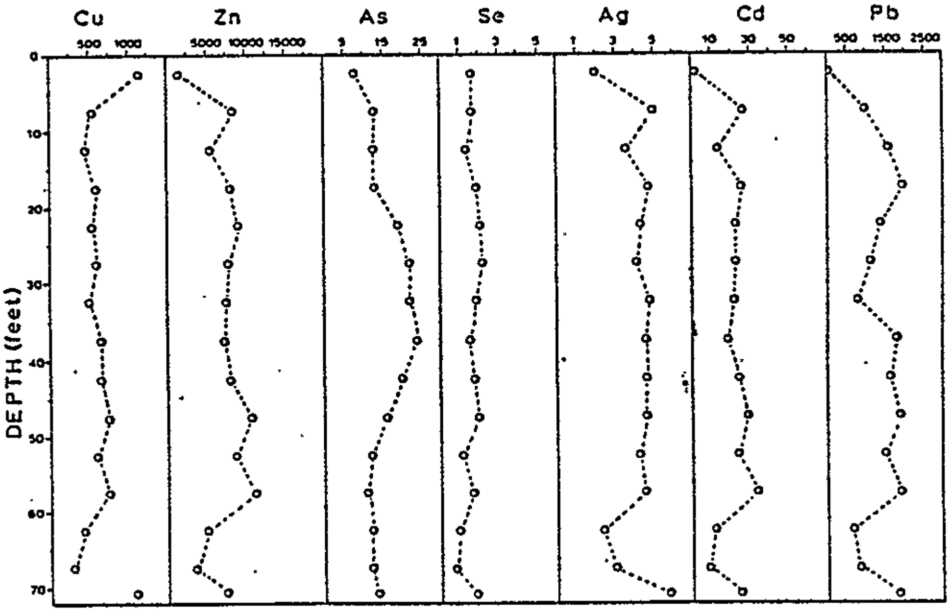
HOLE H4



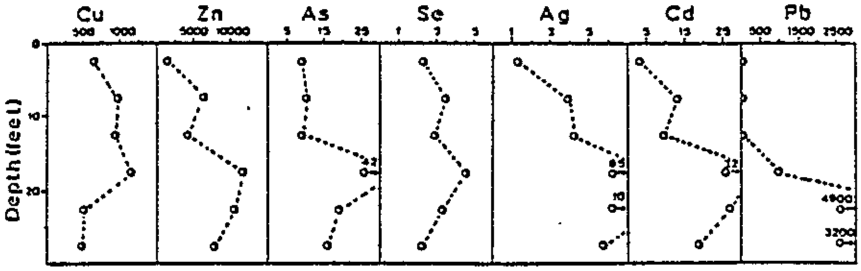
HOLE H5



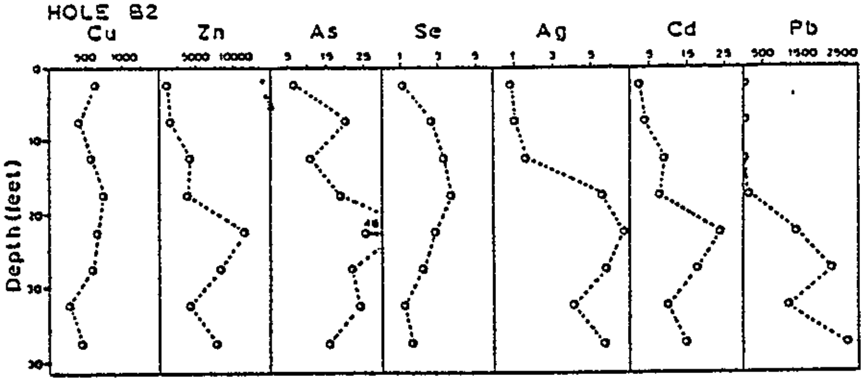
HOLE H6



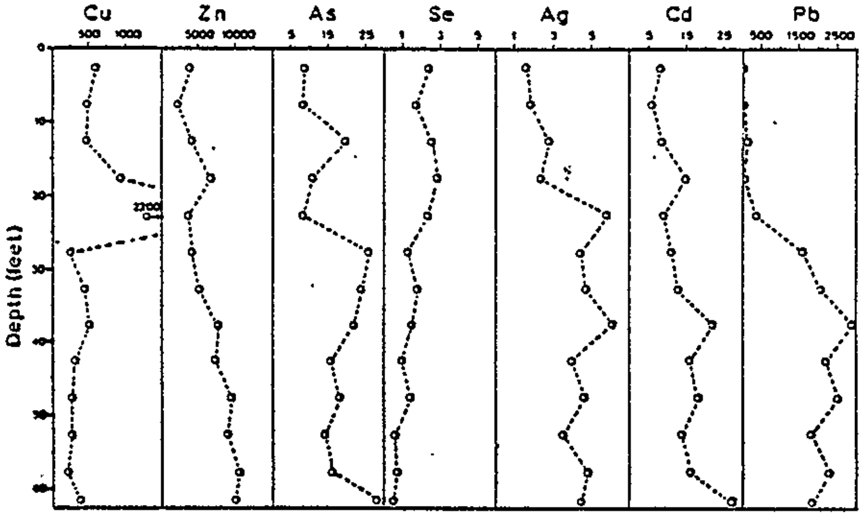
HOLE B1



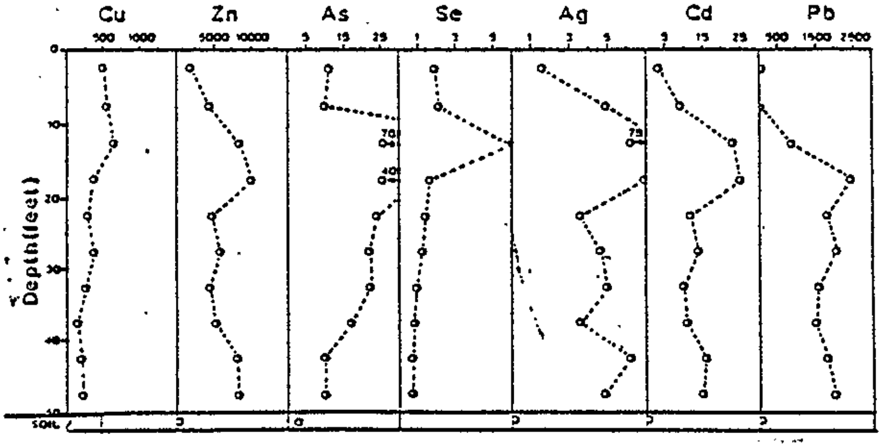
HOLE B2

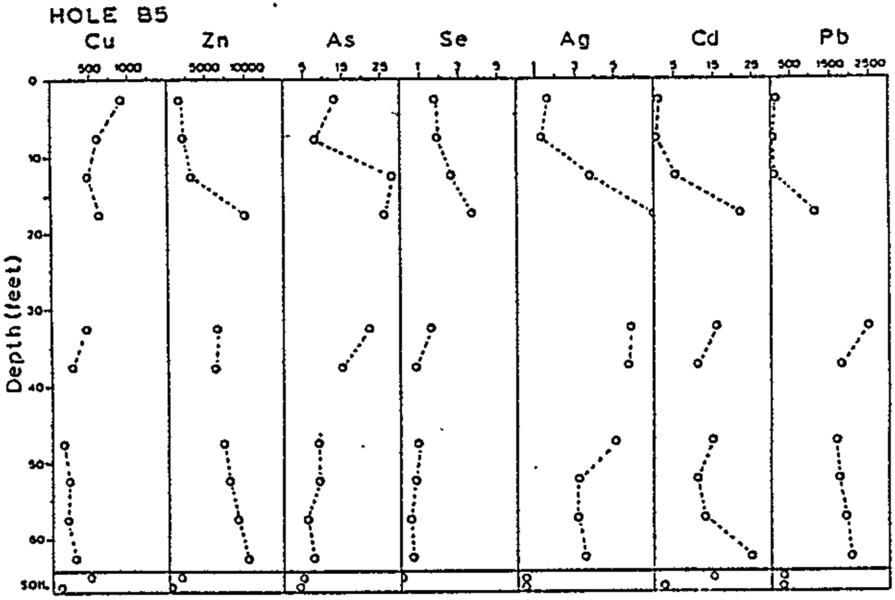


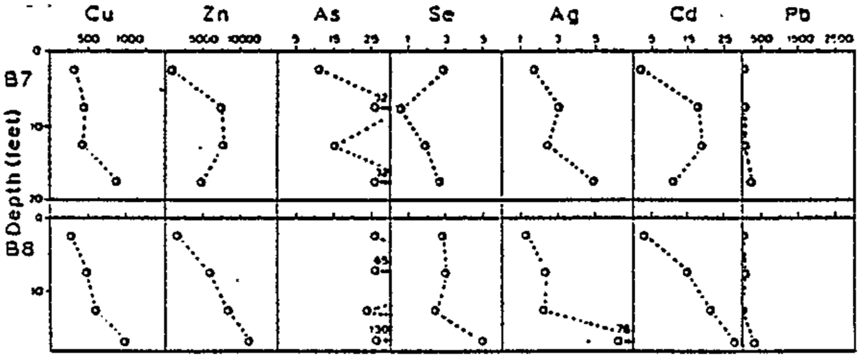
HOLE B3

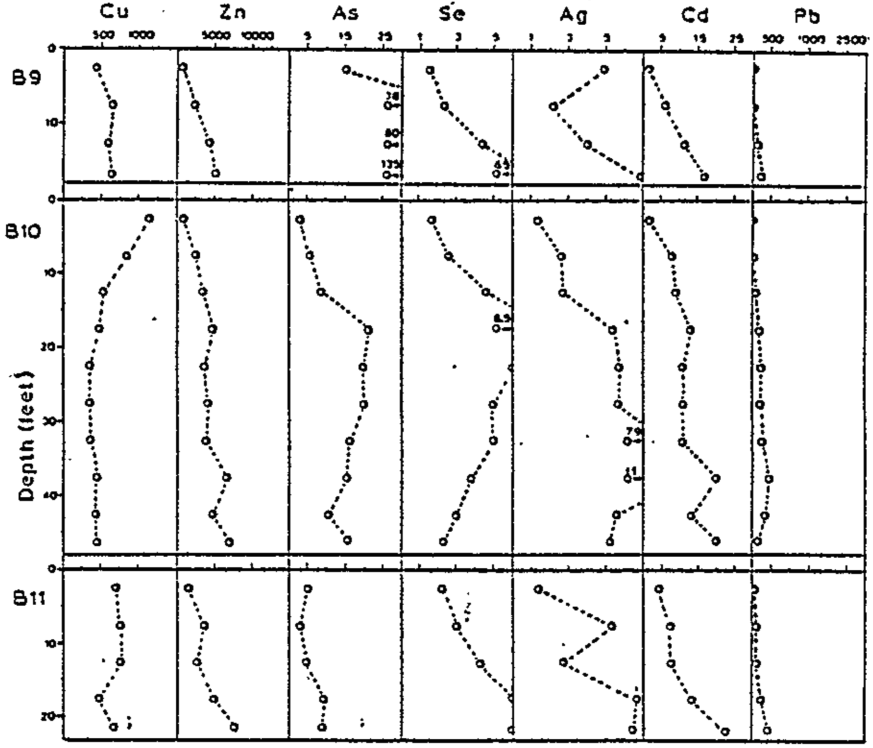


HOLE B4

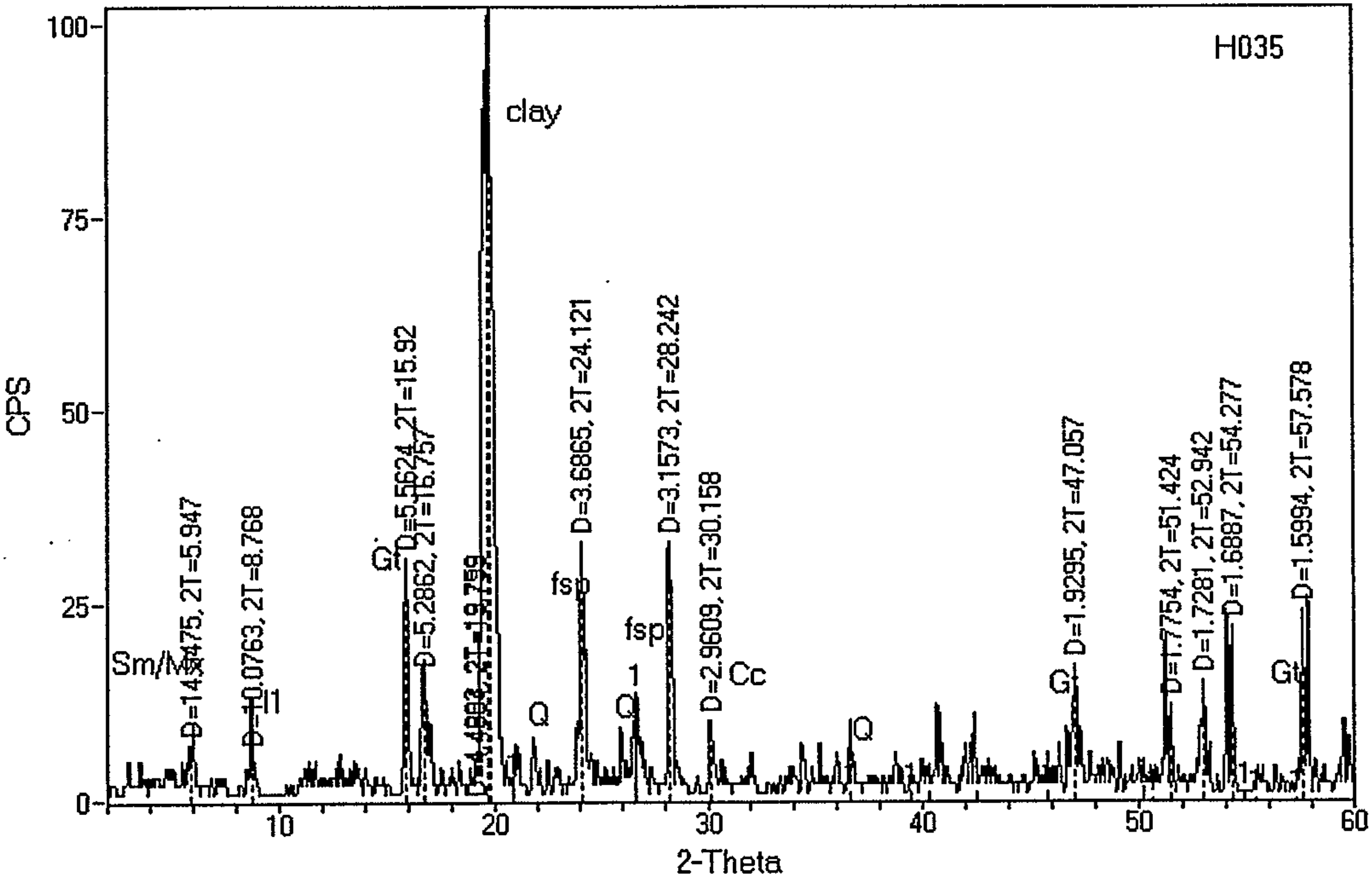



HOLE B5
Cu
Zn
As
Se
Ag
Cd
Pb
500 1000
5000 10000
5 15 25
1 3 5
1 3 5
5 15 25
500 1500 2500
Depth (feet)
0
10
20
30
40
50
60
SOIL


Cu
Zn
As
Se
Ag
Cd
Pb
500 1000
5000 10000
5 15 25
1 3 5
1 3 5
5 15 25
500 1500 2500
B7
B8
Depth (feet)
0
10
20
32
33
85
130
7.8

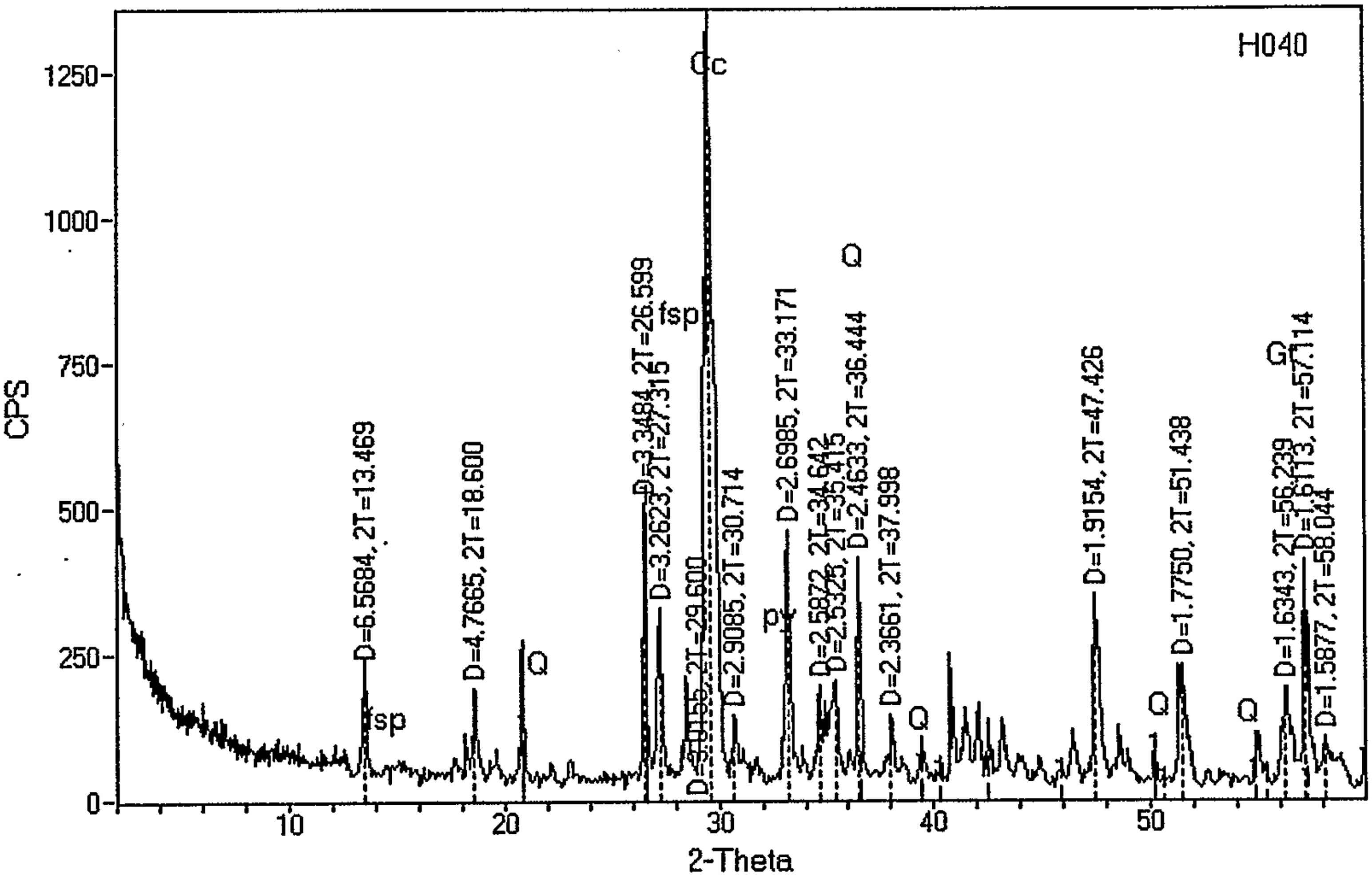

Cu
Zn
As
Se
Ag
Cd
Pb
500 1000
5000 10000
5 15 25
1 3 5
1 3 5
5 15 25
500 1000 2500
B9
B10
B11
Depth (feet)
0
10
20
30
40
38
80
135
6.5
8.5
7.9
11

APPENDIX C
XRD Data

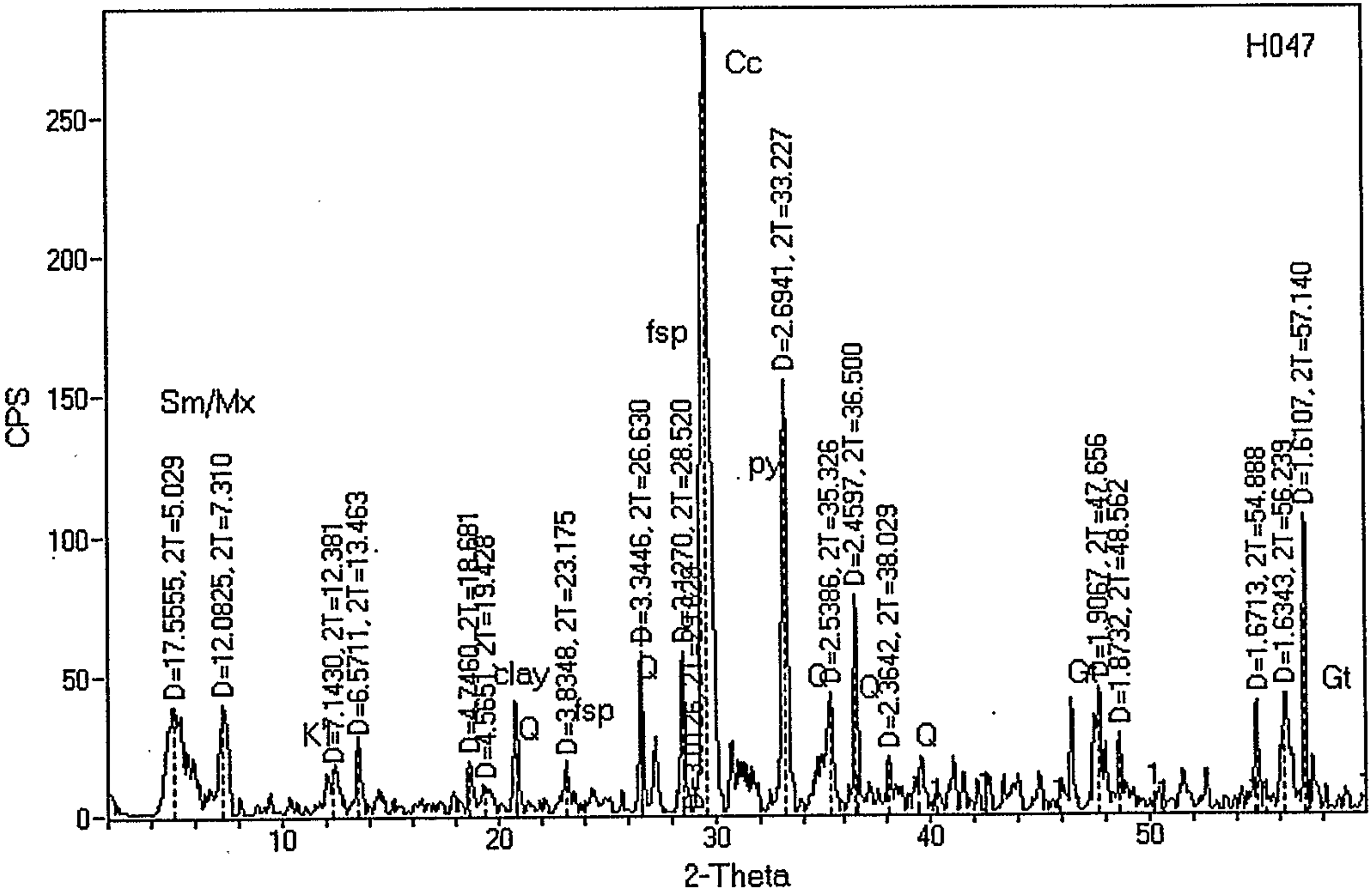


1> 33-1161: Quartz, syn

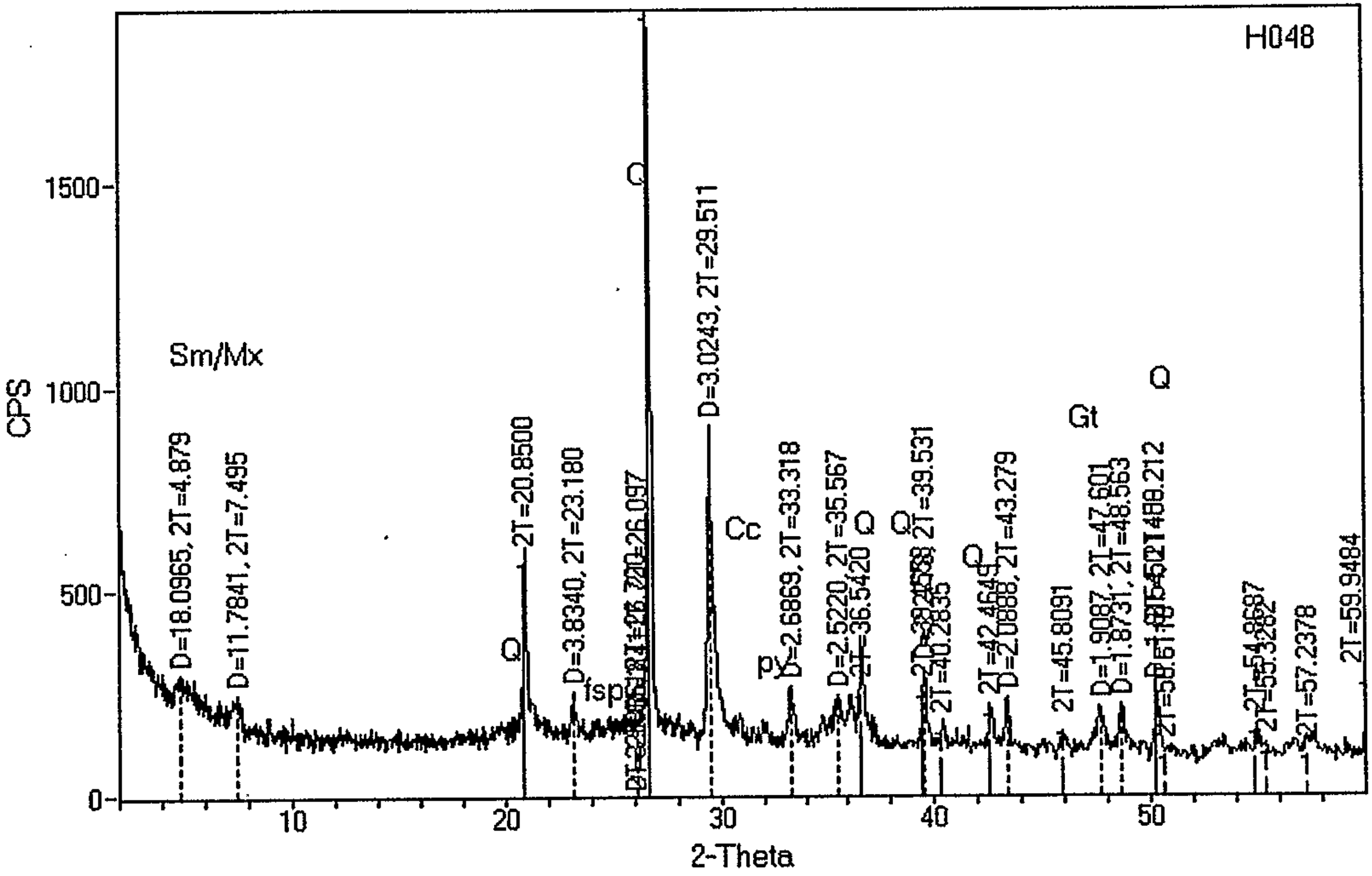
C-3



1> 33-1161: Quartz, syn

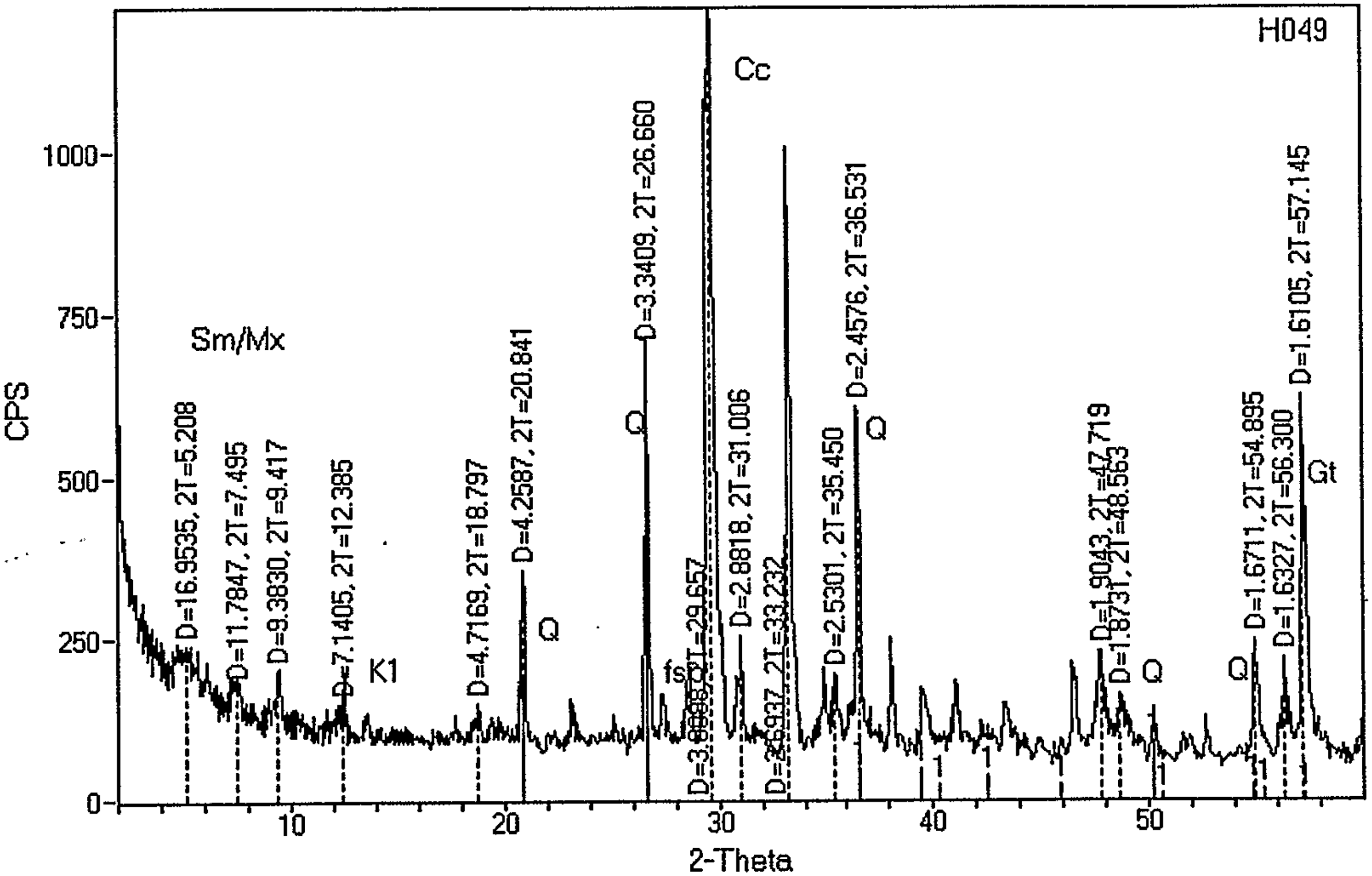


1> 33-1161: Quartz, syn



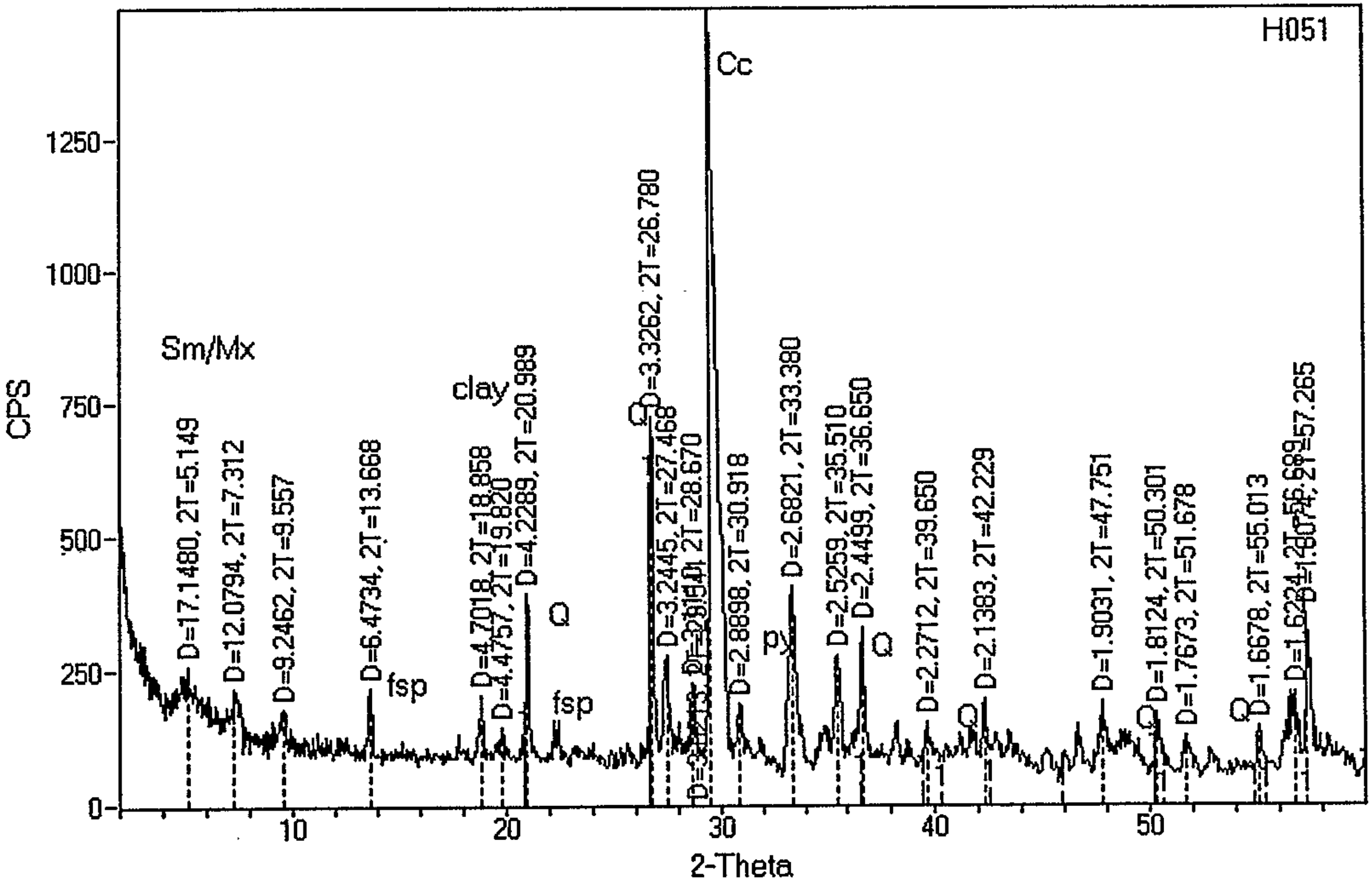
1> 33-1161: Quartz, syn

C-6



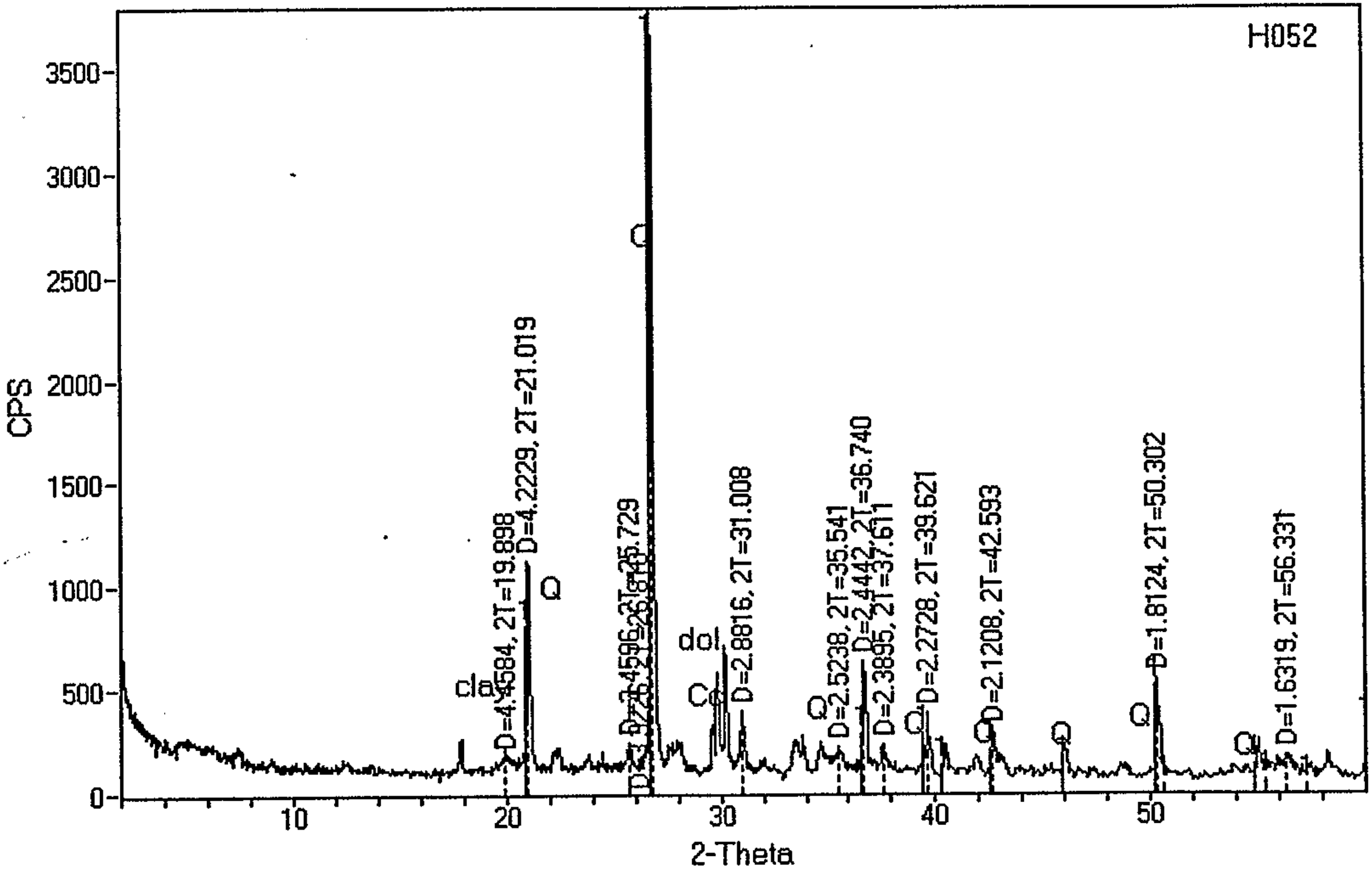
1> 33-1161: Quartz, syn

C-7

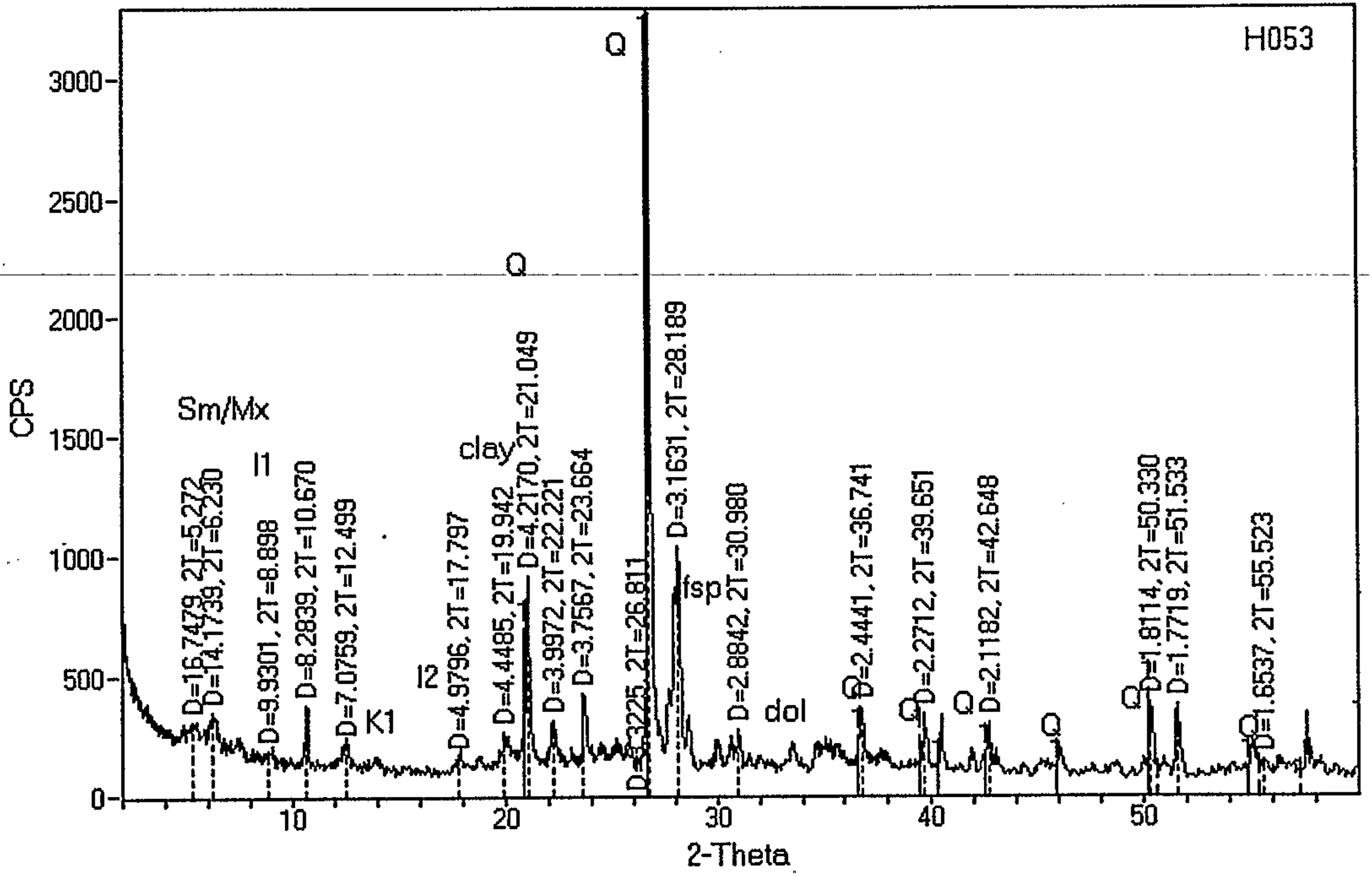


1> 33-1161: Quartz, syn

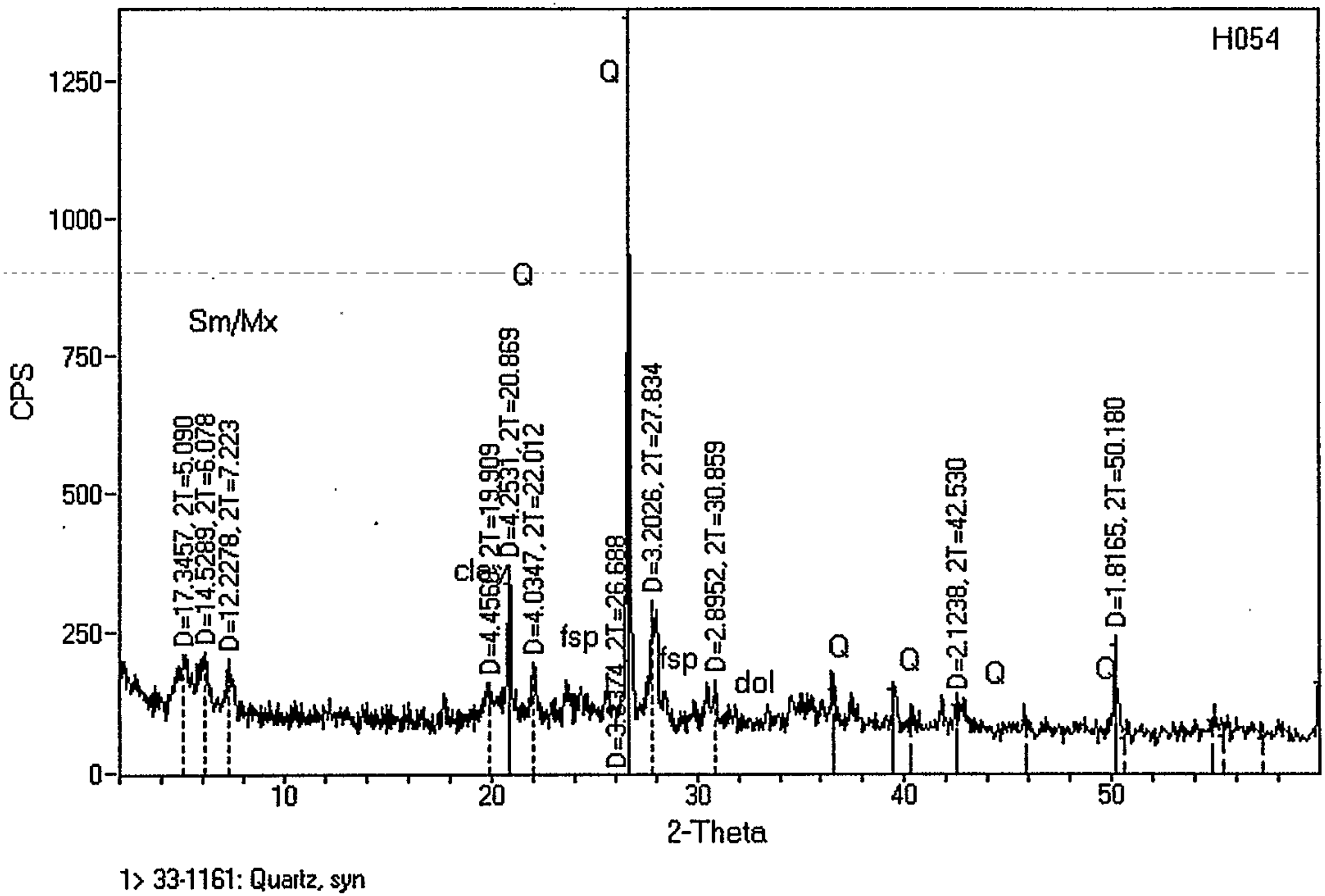
C-8

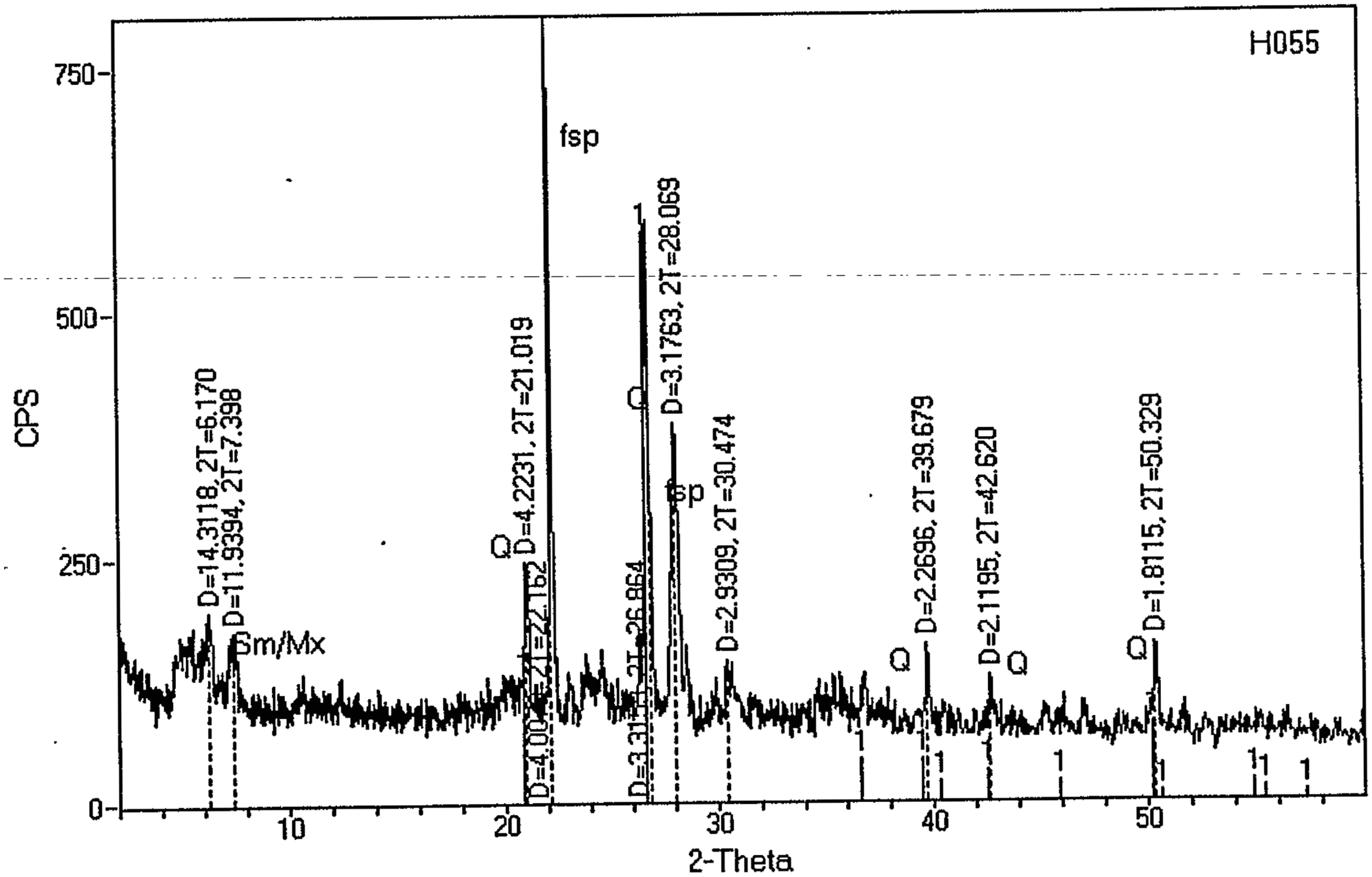


1> 33-1161: Quartz, syn

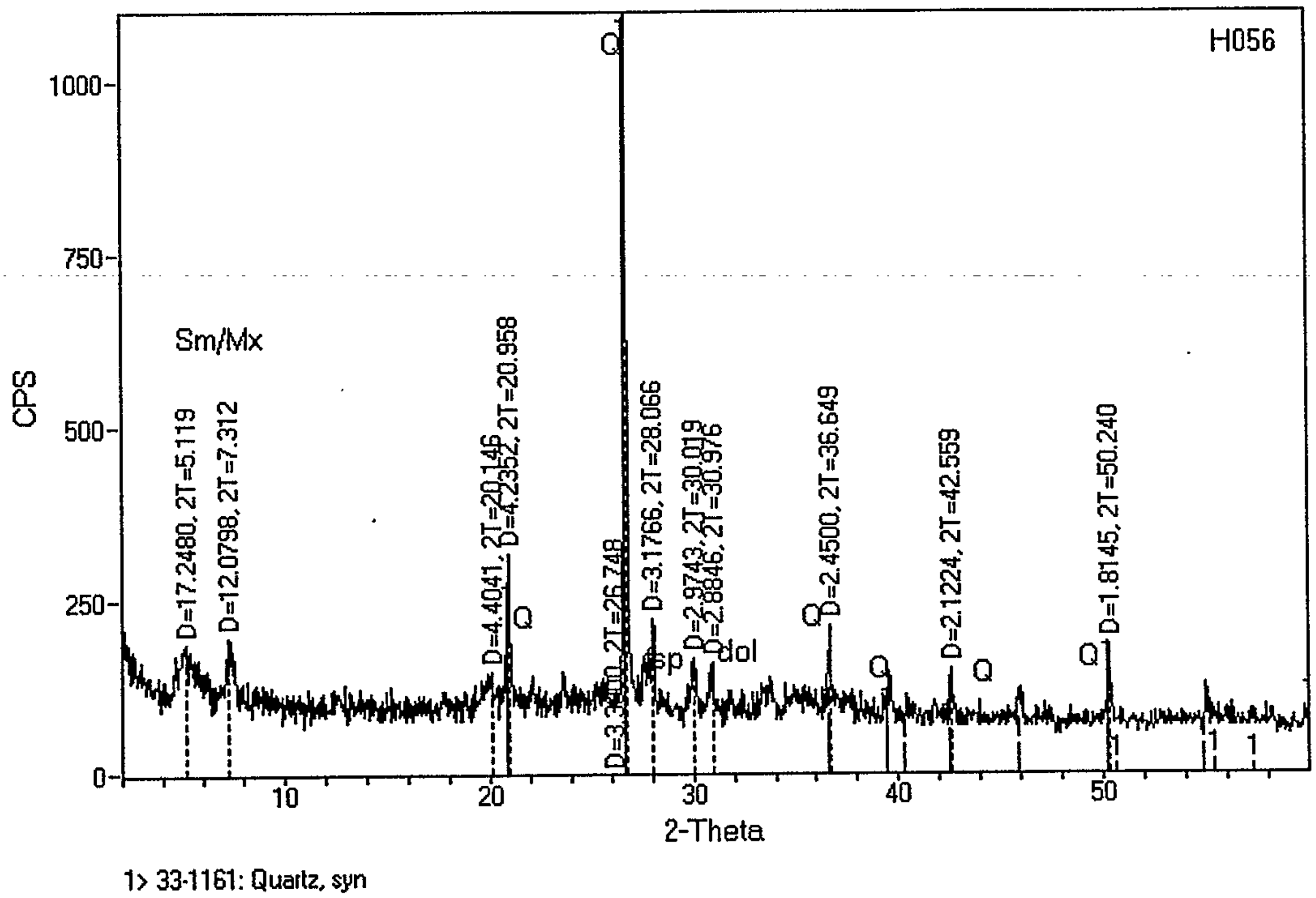


1> 33-1161: Quartz, syn

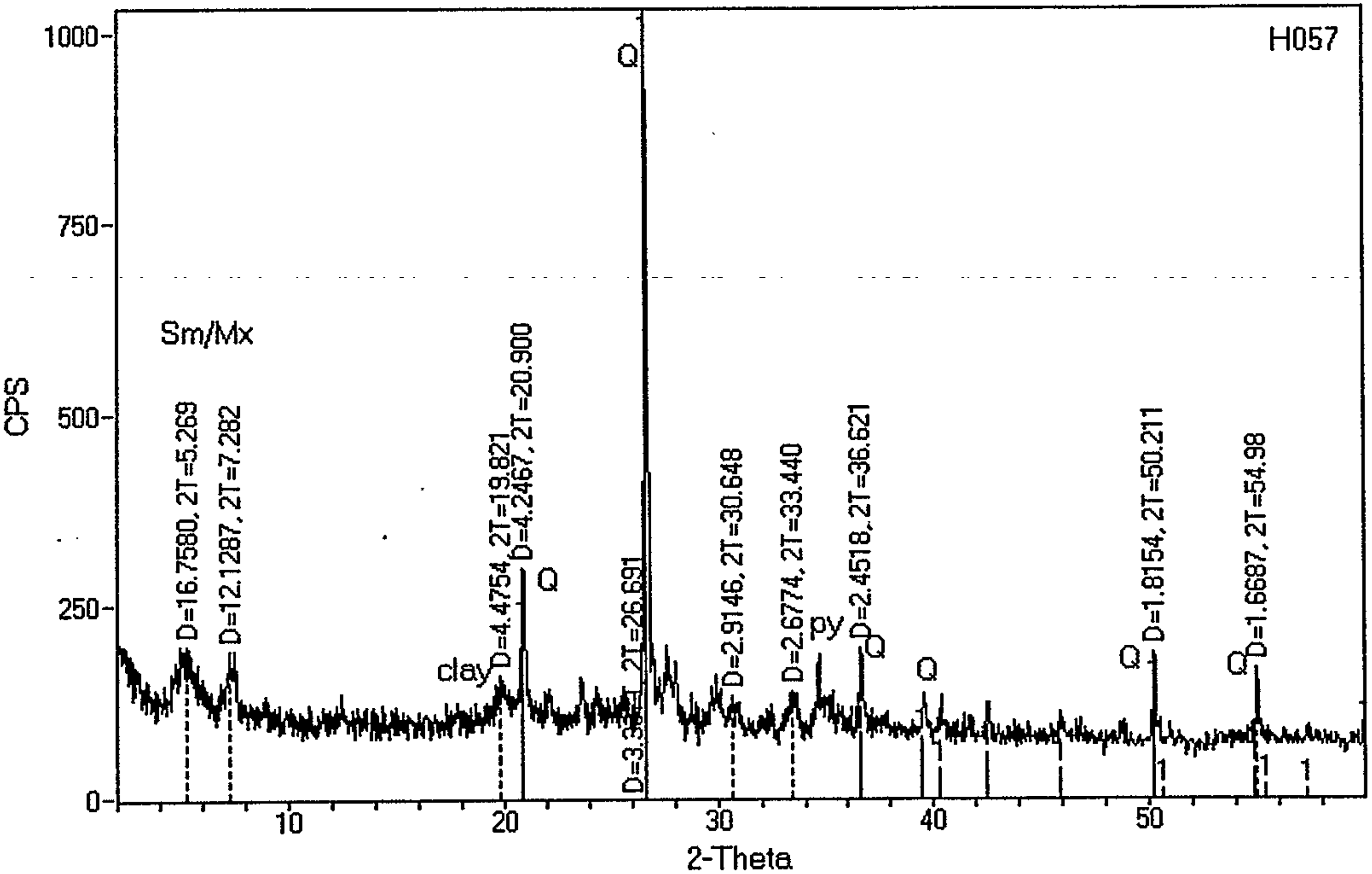

H054
CPS
2-Theta
0
250
500
750
1000
1250
10
20
30
40
50
Sm/Mx
Q
Q
clay
fsp
fsp
dol
Q
Q
Q
Q
D=17.3457, 2T=5.090
D=14.5289, 2T=6.078
D=12.2278, 2T=7.223
D=4.4566, 2T=19.909
D=4.2531, 2T=20.869
D=4.0347, 2T=22.012
D=3.3374, 2T=26.688
D=3.2026, 2T=27.834
D=2.8952, 2T=30.859
D=2.1238, 2T=42.530
D=1.8165, 2T=50.180
1> 33-1161: Quartz, syn



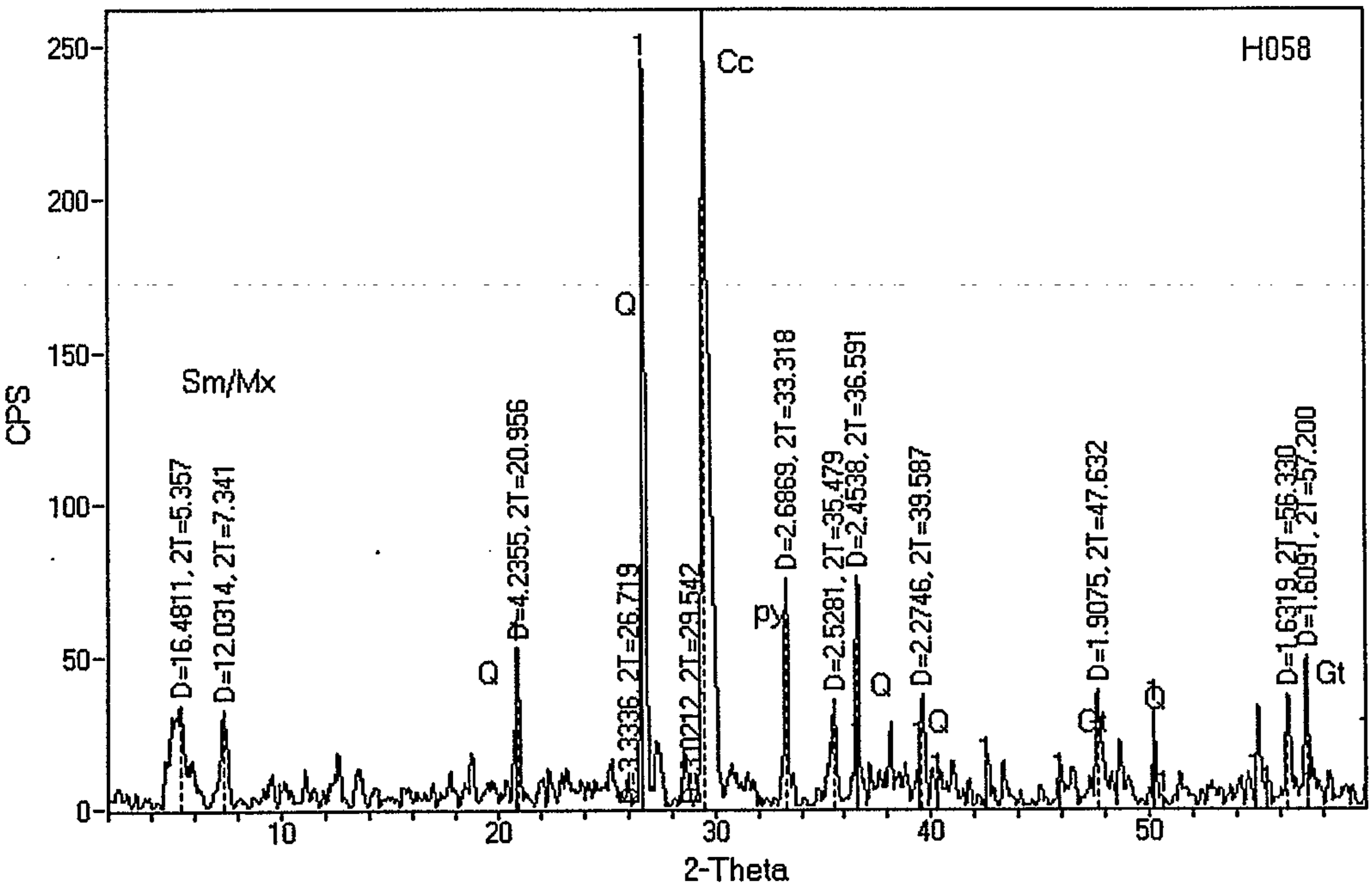
1> 33-1161: Quartz, syn


H056
Sm/Mx
CPS
1000
750
500
250
0
2-Theta
10
20
30
40
50
Q
D=17.2480, 2T=5.119
D=12.0798, 2T=7.312
D=4.4041, 2T=20.146
D=4.2352, 2T=20.958
D=3.3300, 2T=26.748
D=3.1766, 2T=28.066
D=2.9743, 2T=30.019
D=2.8846, 2T=30.976
D=2.4500, 2T=36.649
D=2.1224, 2T=42.559
D=1.8145, 2T=50.240
sp
dol
1
1> 33-1161: Quartz, syn

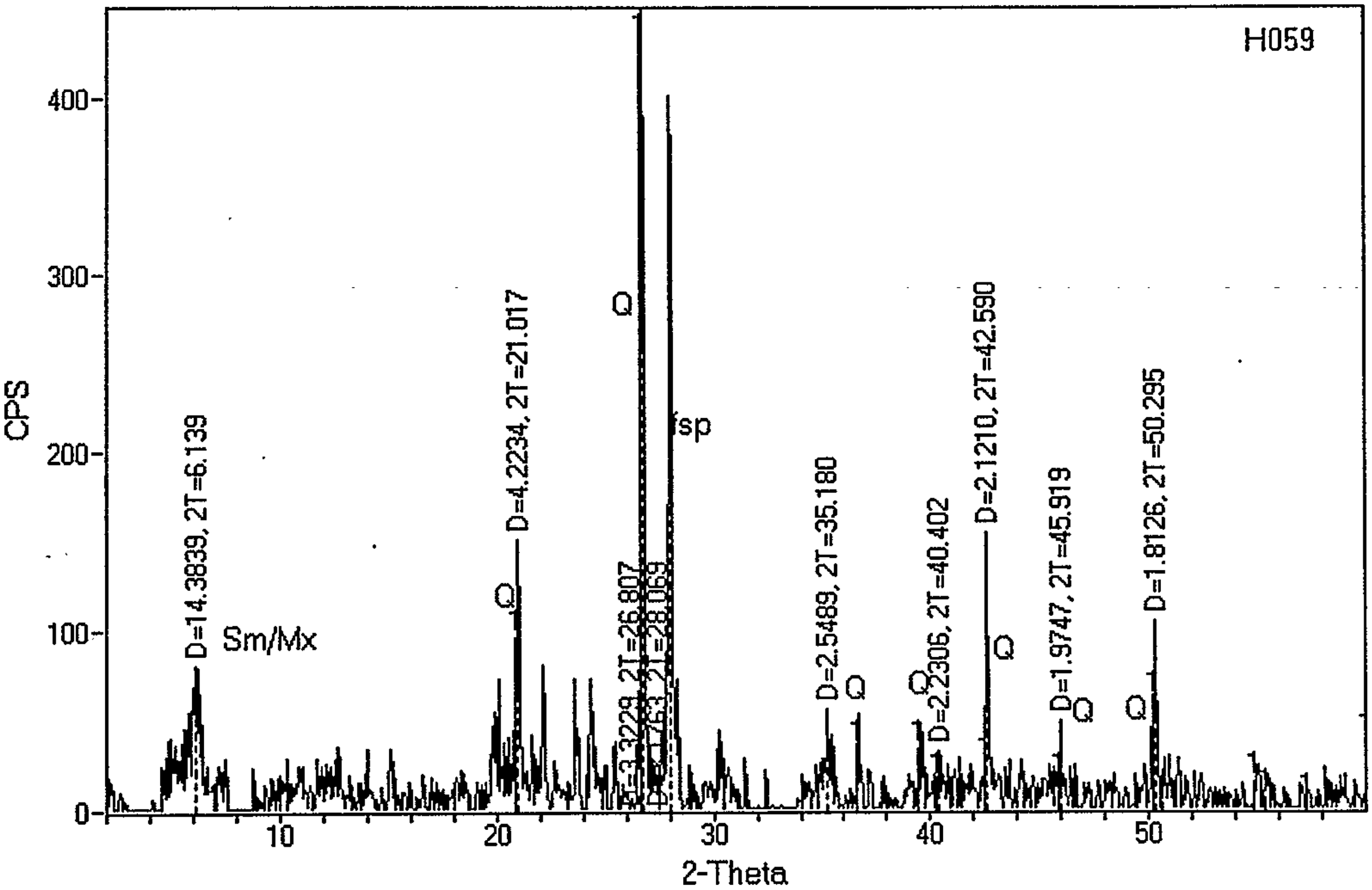
C-13



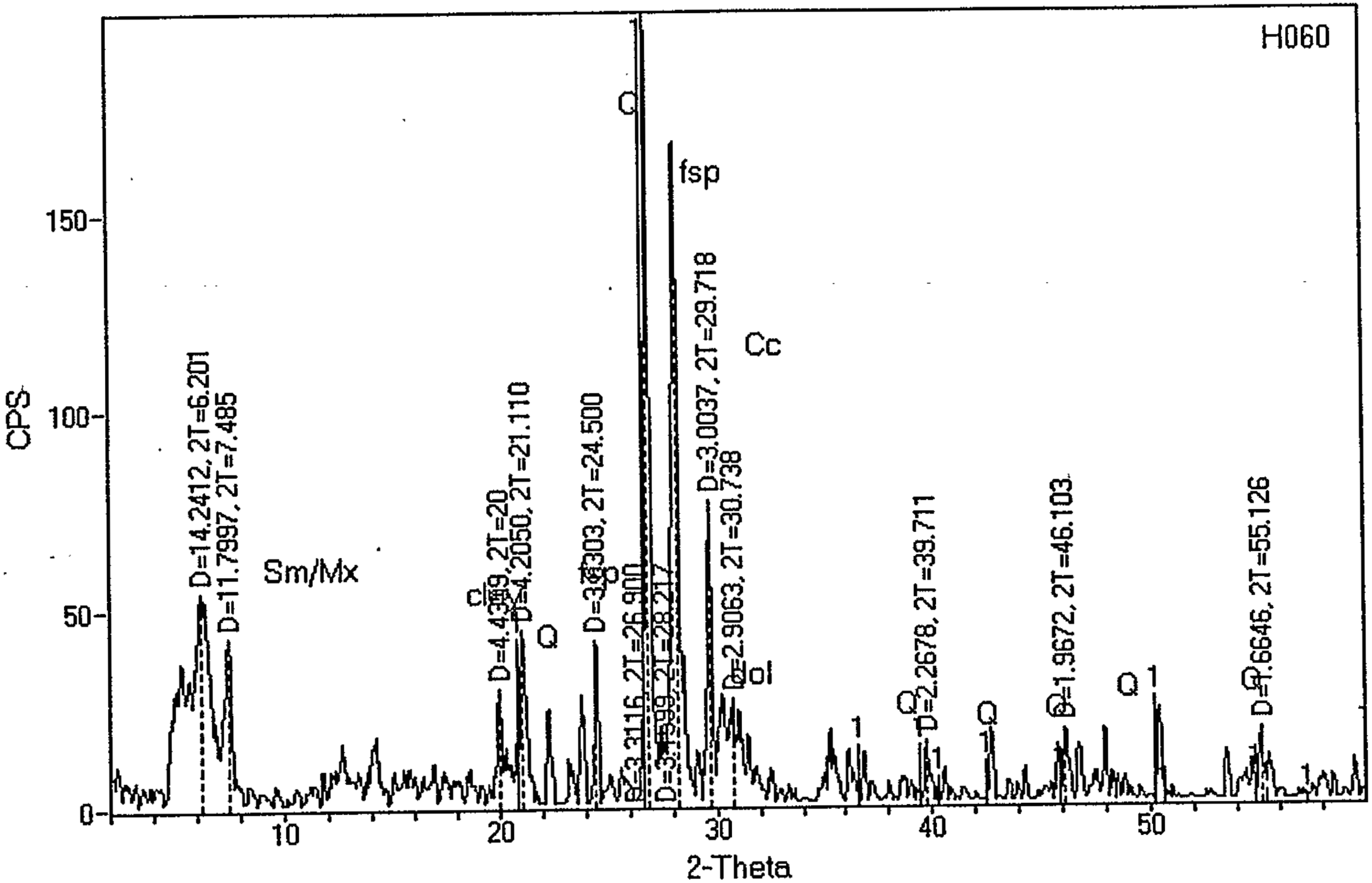
1> 33-1161: Quartz, syn



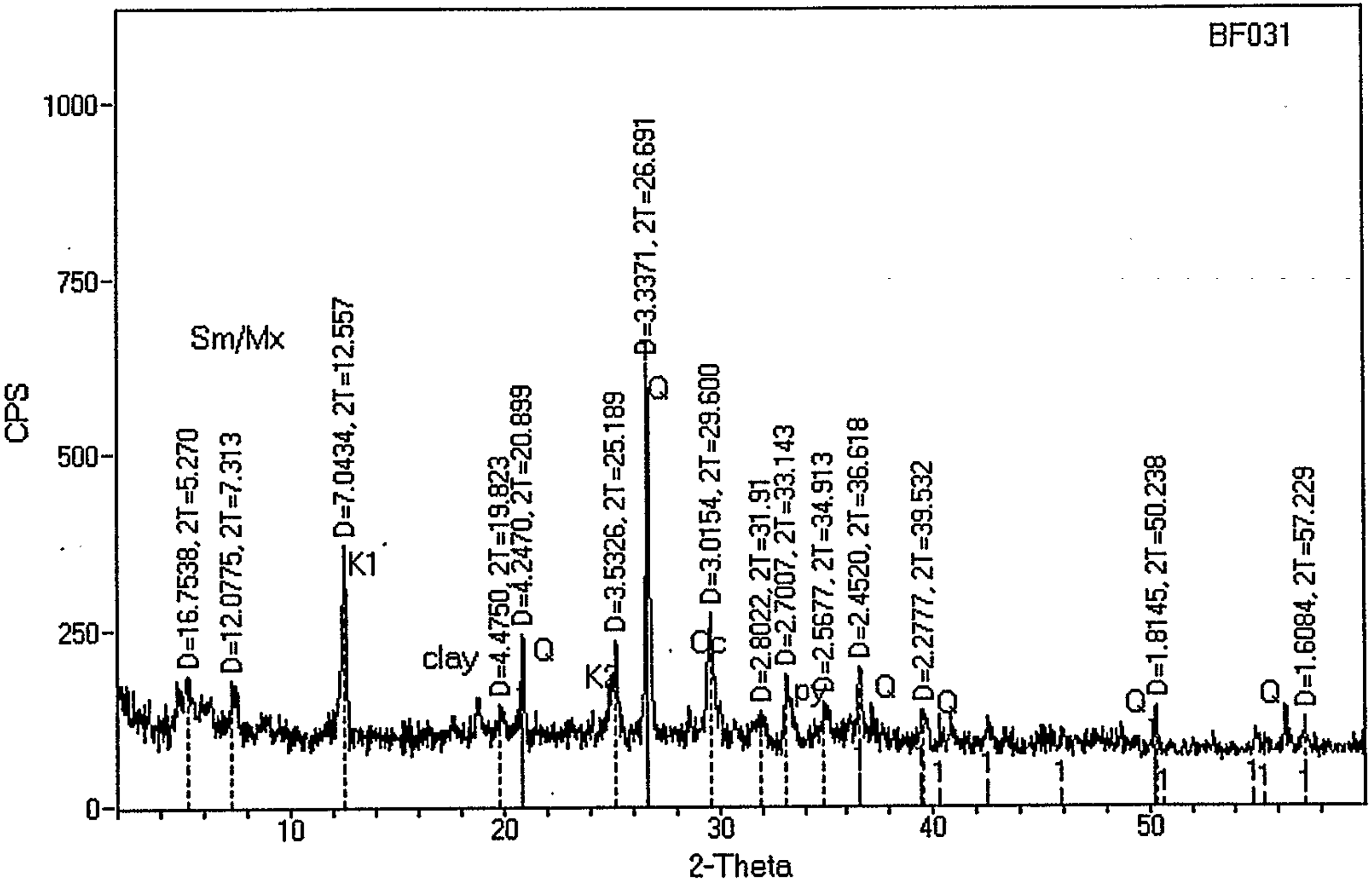
1> 33-1161: Quartz, syn



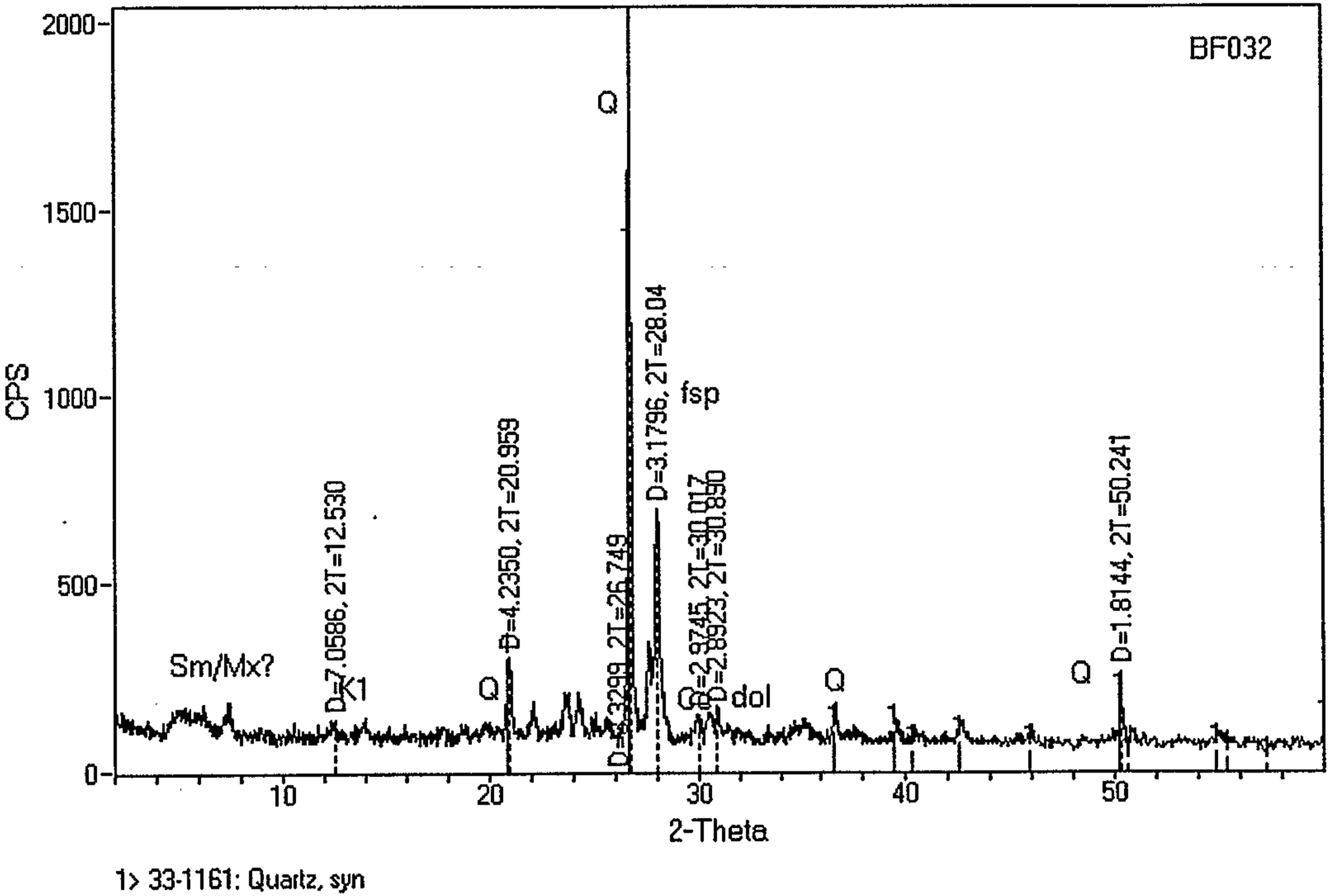
1> 33-1161: Quartz, syn

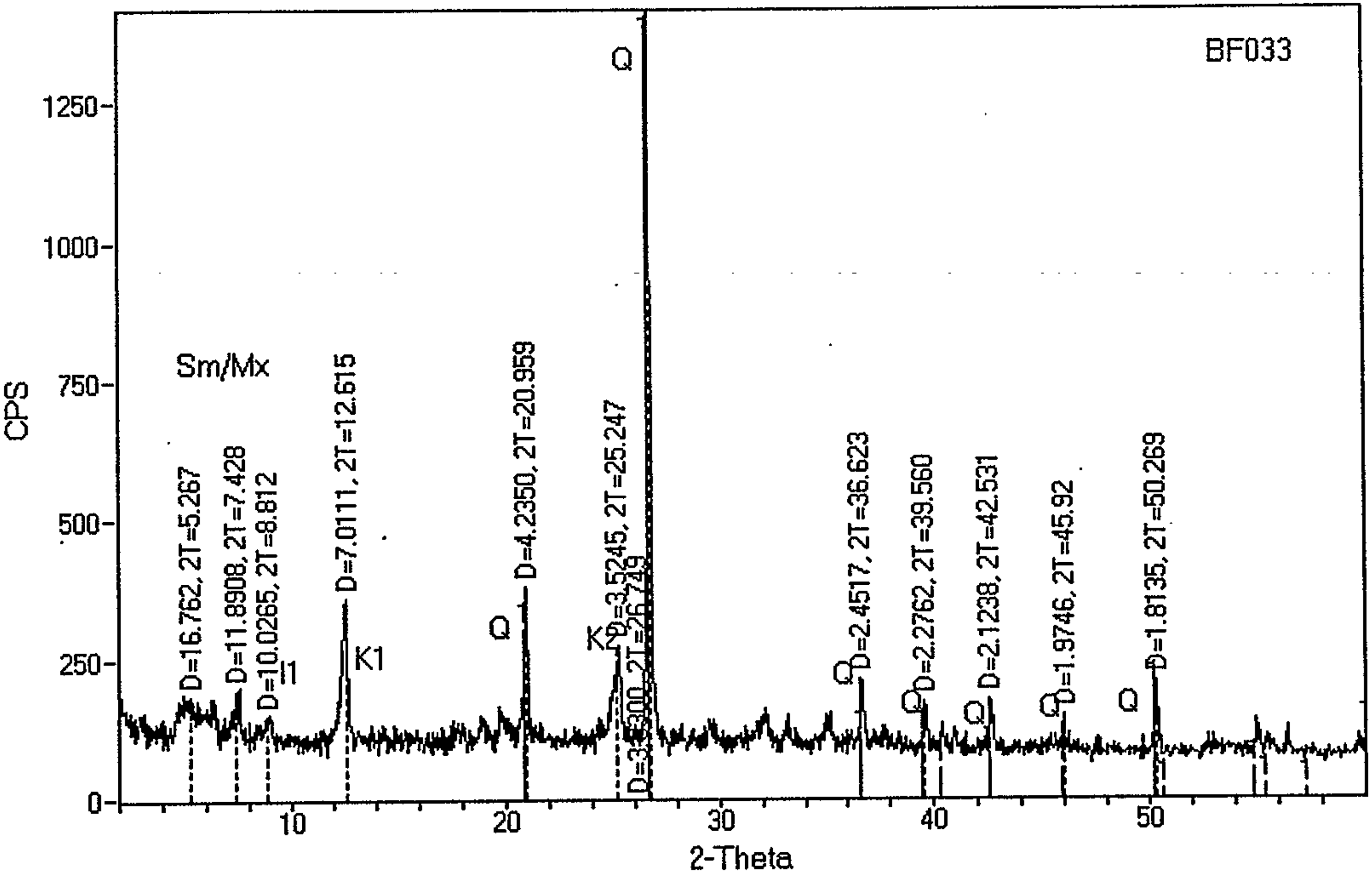


1> 33-1161: Quartz, syn

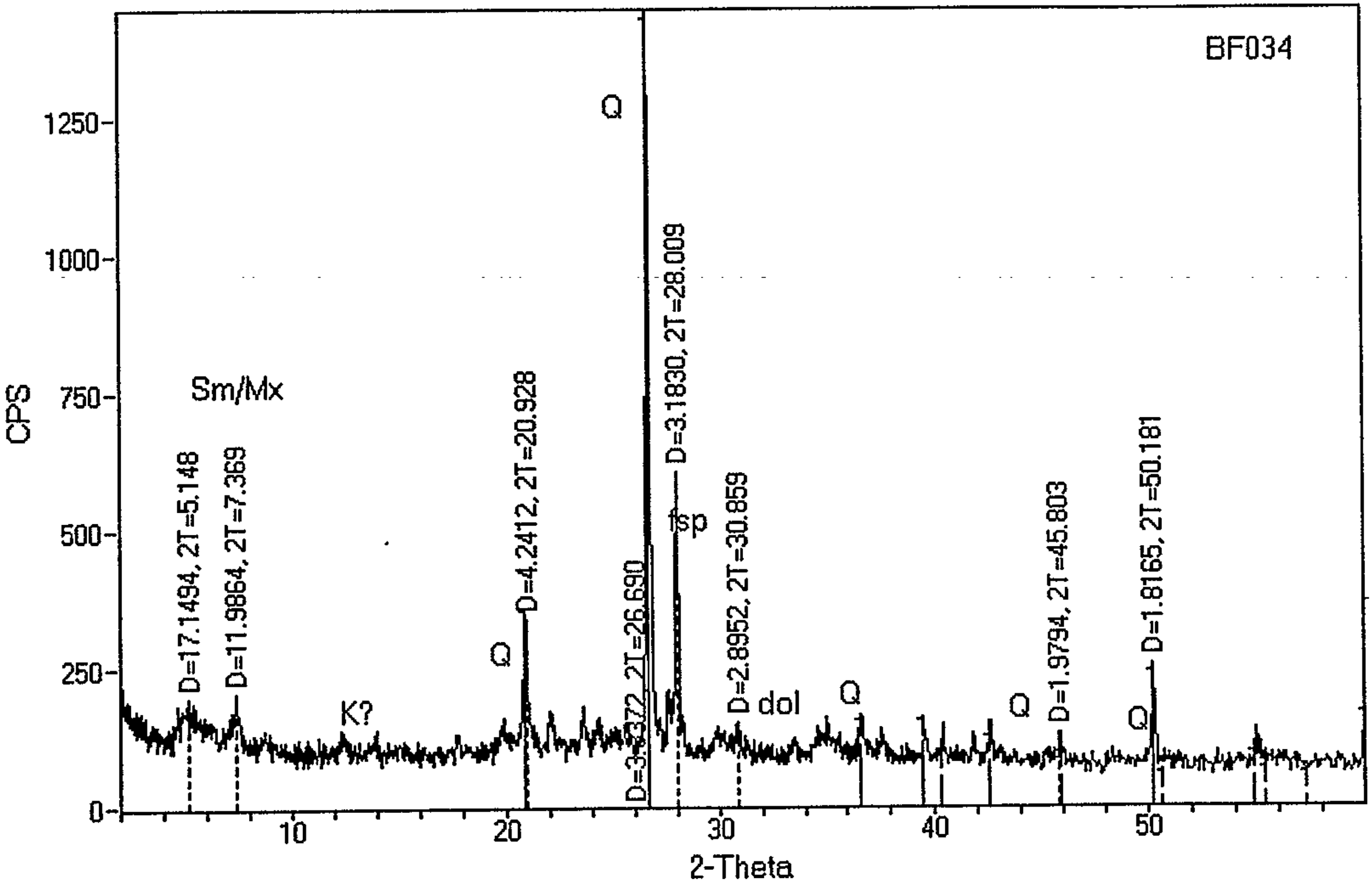


1> 33-1161: Quartz, syn

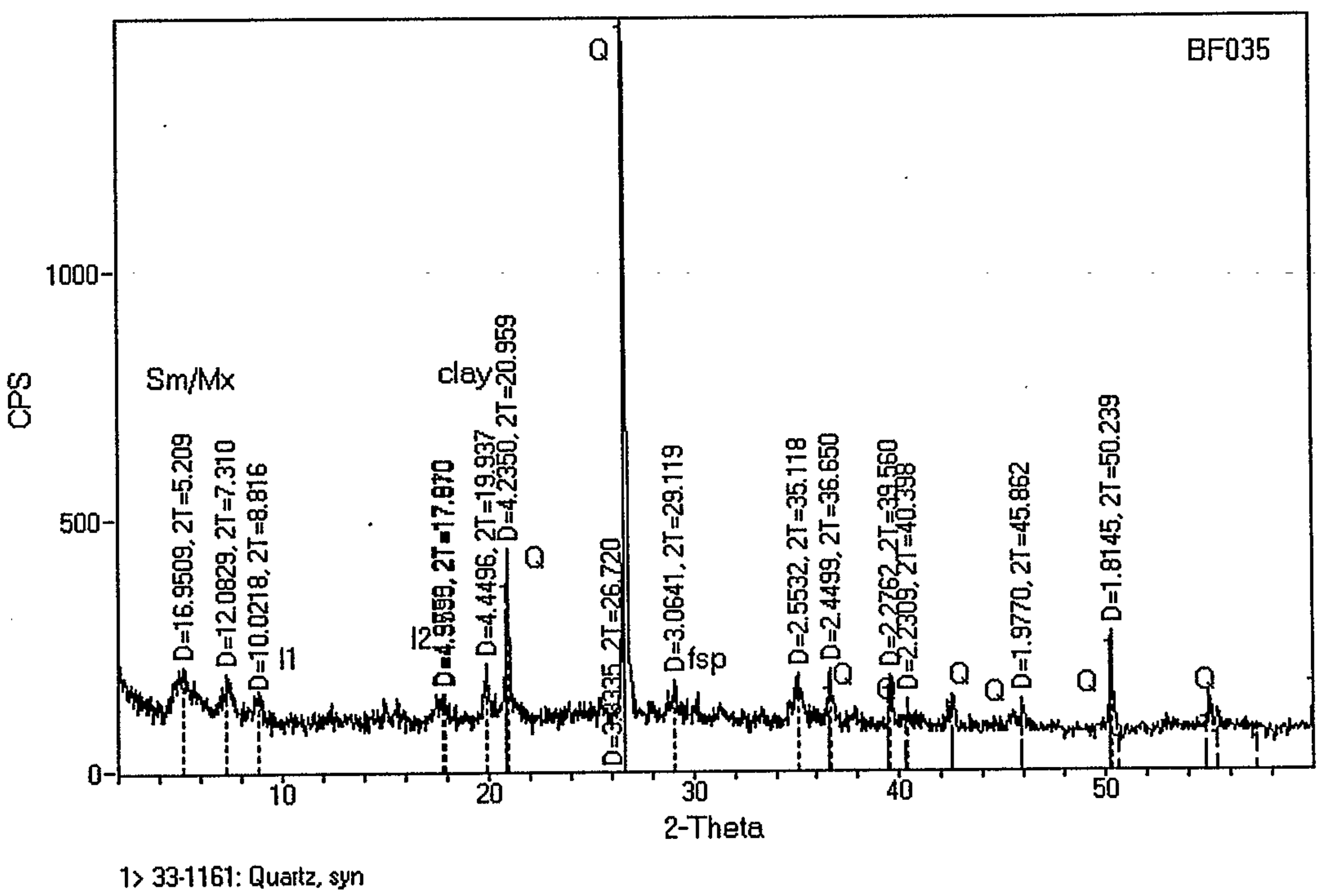

BF032
CPS
2000
1500
1000
500
0
2-Theta
10
20
30
40
50
Q
Q
Q
Q
Q
Sm/Mx?
K1
fsp
dol
D=7.0586, 2T=12.530
D=4.2350, 2T=20.959
D=3.3299, 2T=26.749
D=3.1796, 2T=28.04
D=2.9745, 2T=30.017
D=2.8923, 2T=30.890
D=1.8144, 2T=50.241
1> 33-1161: Quartz, syn

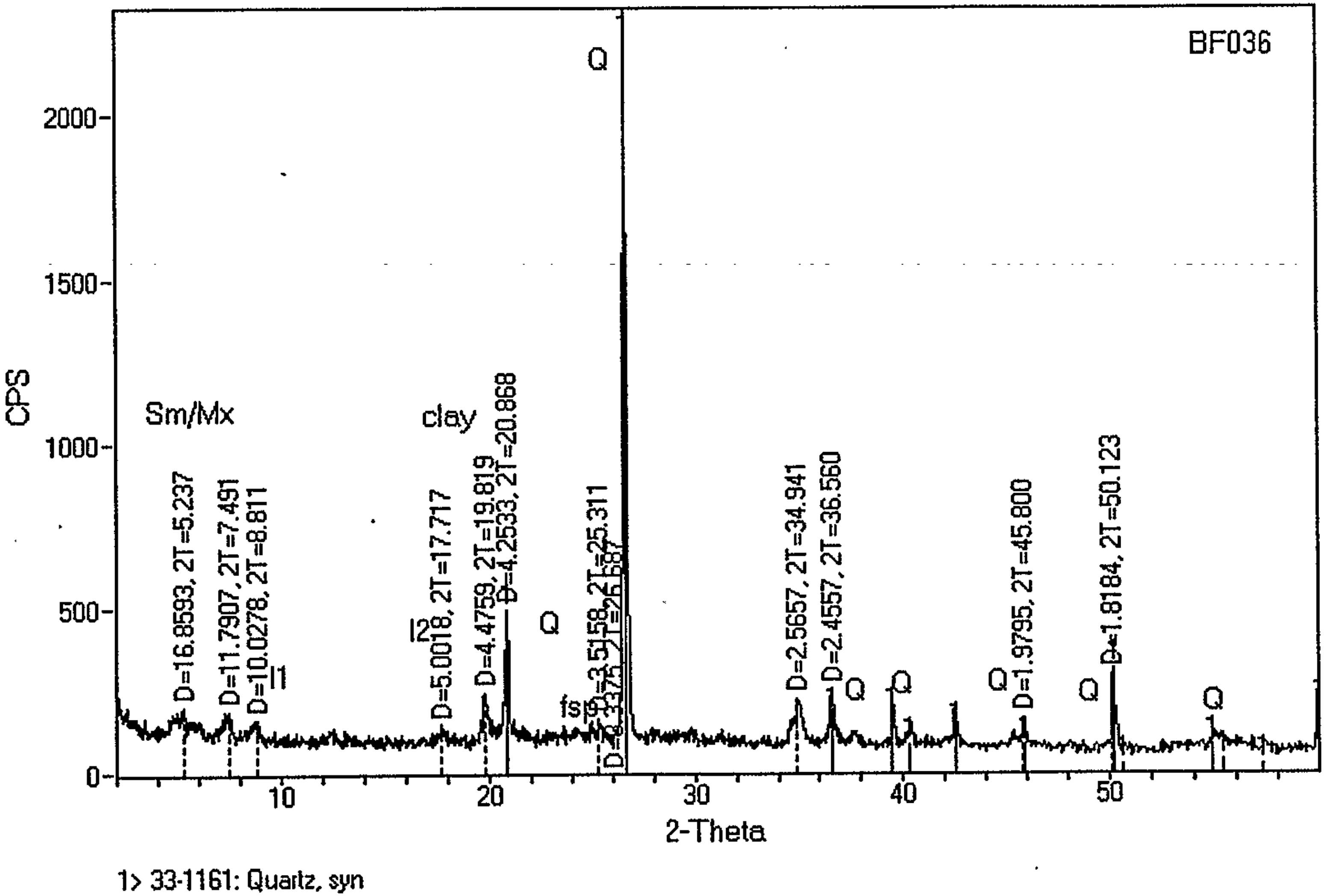


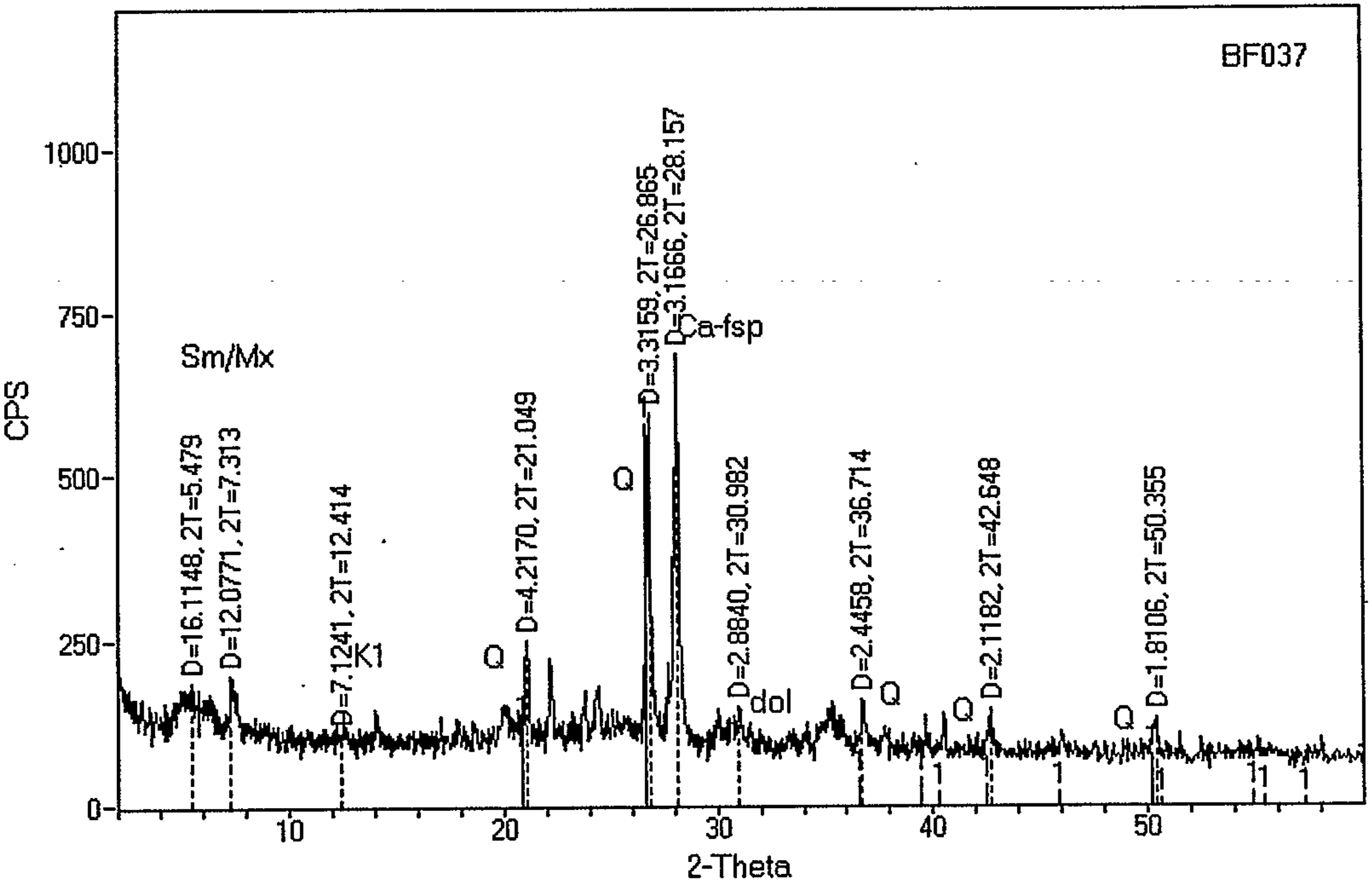
1> 33-1161: Quartz, syn



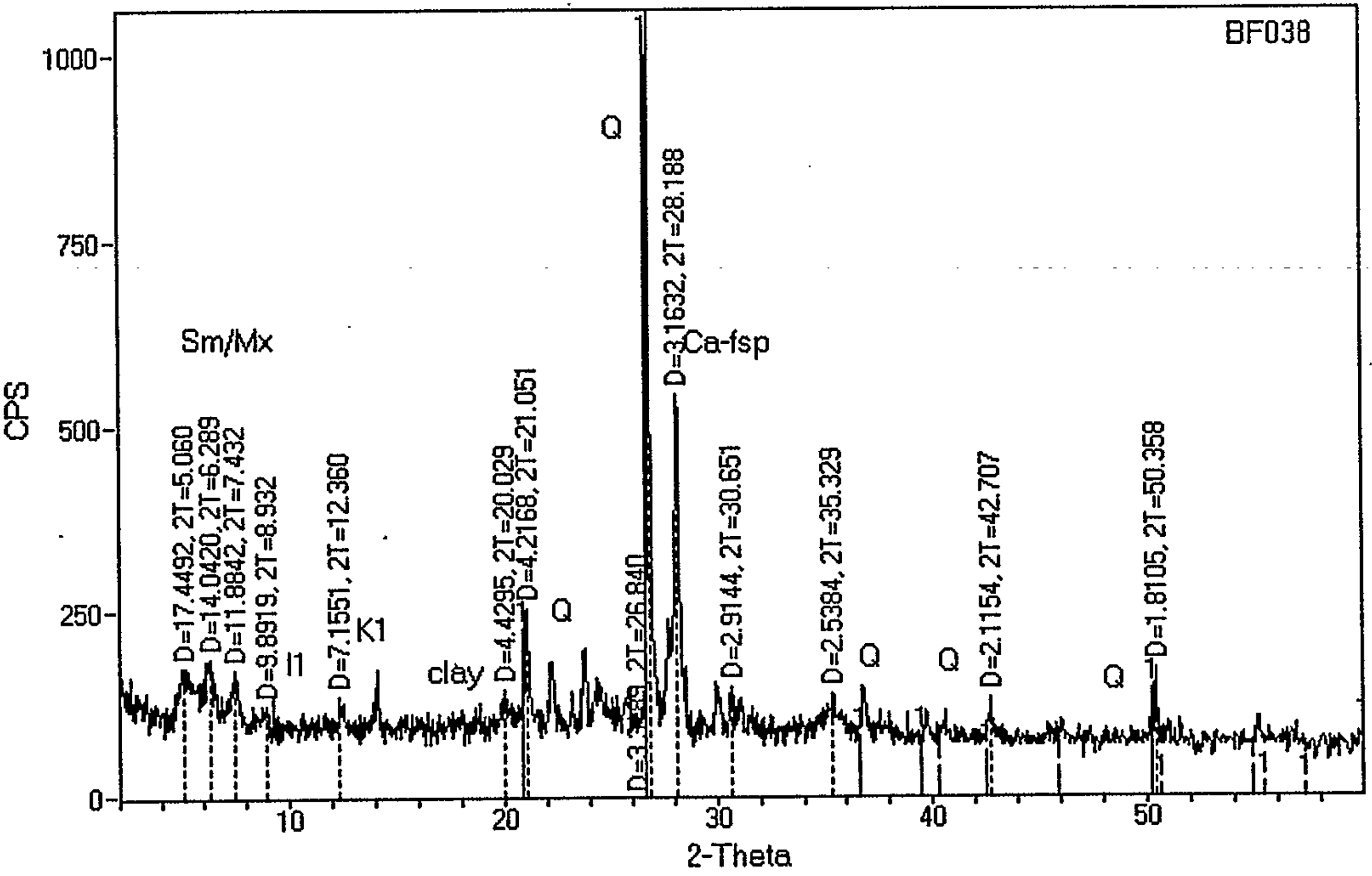
1> 33-1161: Quartz, syn


BF035
Q
CPS
1000
500
0
Sm/Mx
clay
D=16.9509, 2T=5.209
D=12.0829, 2T=7.310
D=10.0218, 2T=8.816
I1
I2
D=4.9599, 2T=17.870
D=4.4496, 2T=19.937
D=4.2350, 2T=20.959
Q
D=3.3335, 2T=26.720
D=3.0641, 2T=29.119
fsp
D=2.5532, 2T=35.118
D=2.4499, 2T=36.650
Q
D=2.2762, 2T=39.560
D=2.2309, 2T=40.398
Q
Q
Q
D=1.9770, 2T=45.862
Q
D=1.8145, 2T=50.239
Q
10
20
30
40
50
2-Theta
1> 33-1161: Quartz, syn

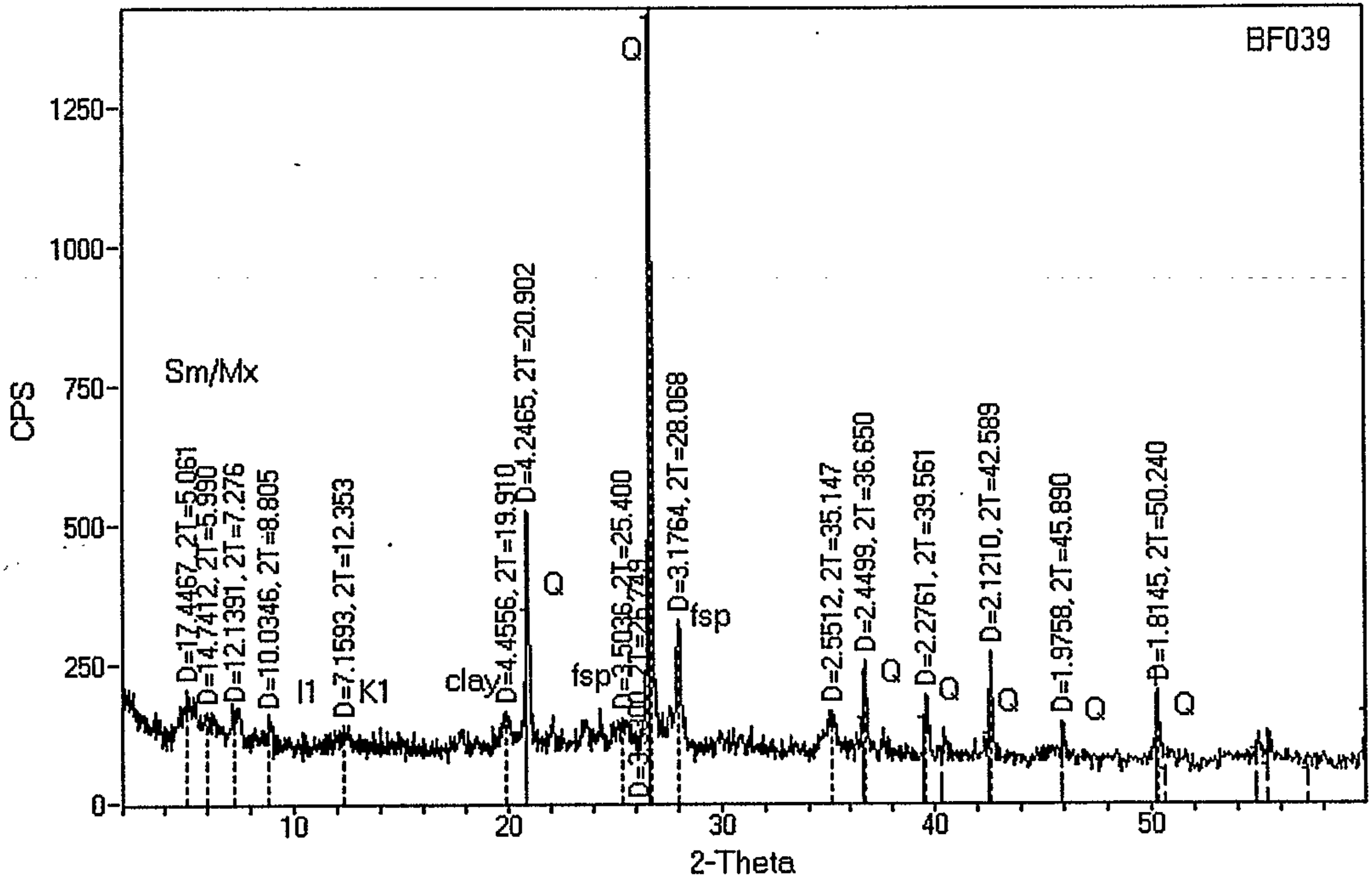

BF036
Q
CPS
2000
1500
1000
500
0
10
20
30
40
50
2-Theta
Sm/Mx
clay
I1
I2
Q
fsp
Q
Q
Q
Q
Q
D=16.8593, 2T=5.237
D=11.7907, 2T=7.491
D=10.0278, 2T=8.811
D=5.0018, 2T=17.717
D=4.4759, 2T=19.819
D=4.2533, 2T=20.868
D=3.5158, 2T=25.311
D=3.3375, 2T=26.687
D=2.5657, 2T=34.941
D=2.4557, 2T=36.560
D=1.9795, 2T=45.800
D=1.8184, 2T=50.123
1> 33-1161: Quartz, syn



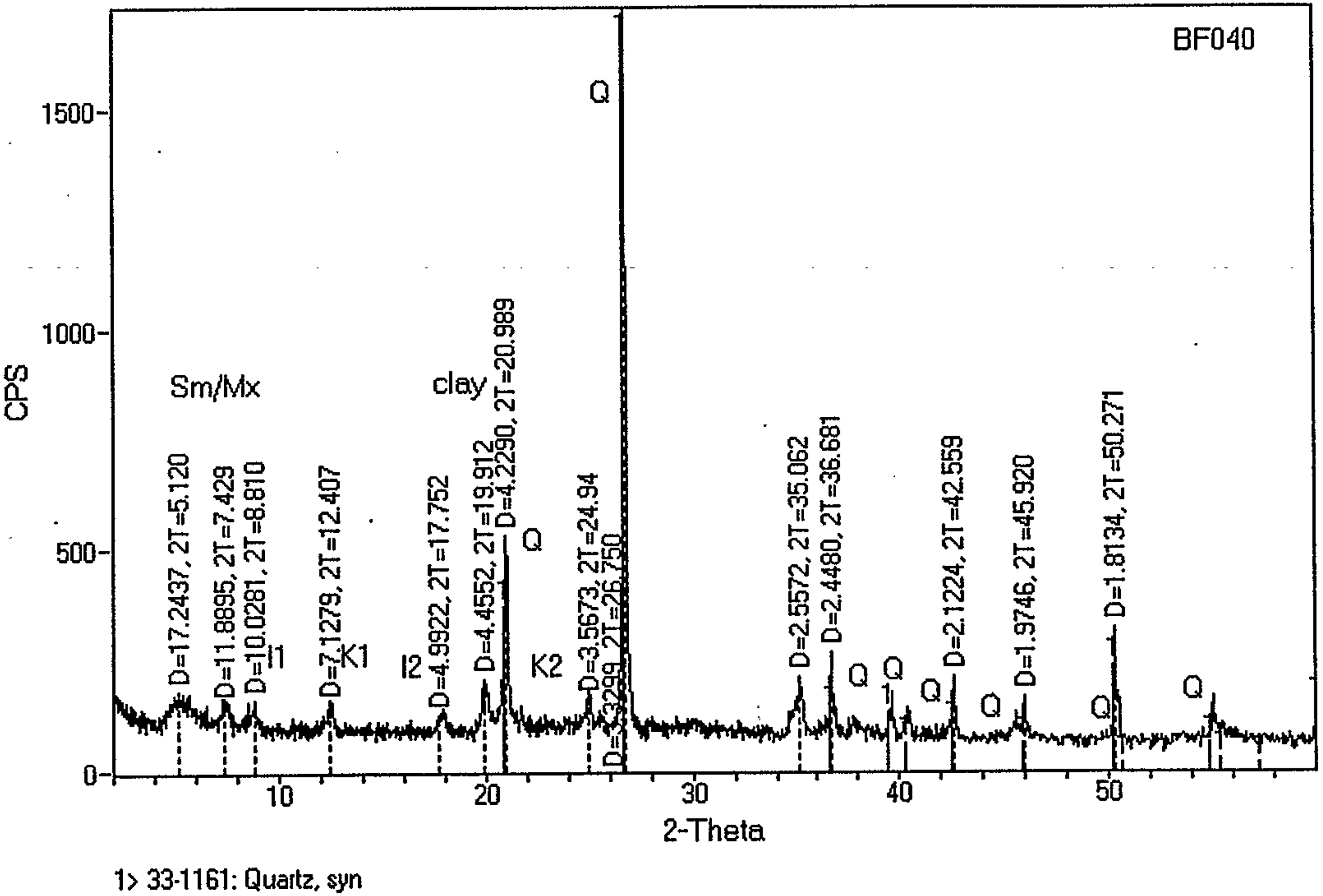
1> 33-1161: Quartz, syn

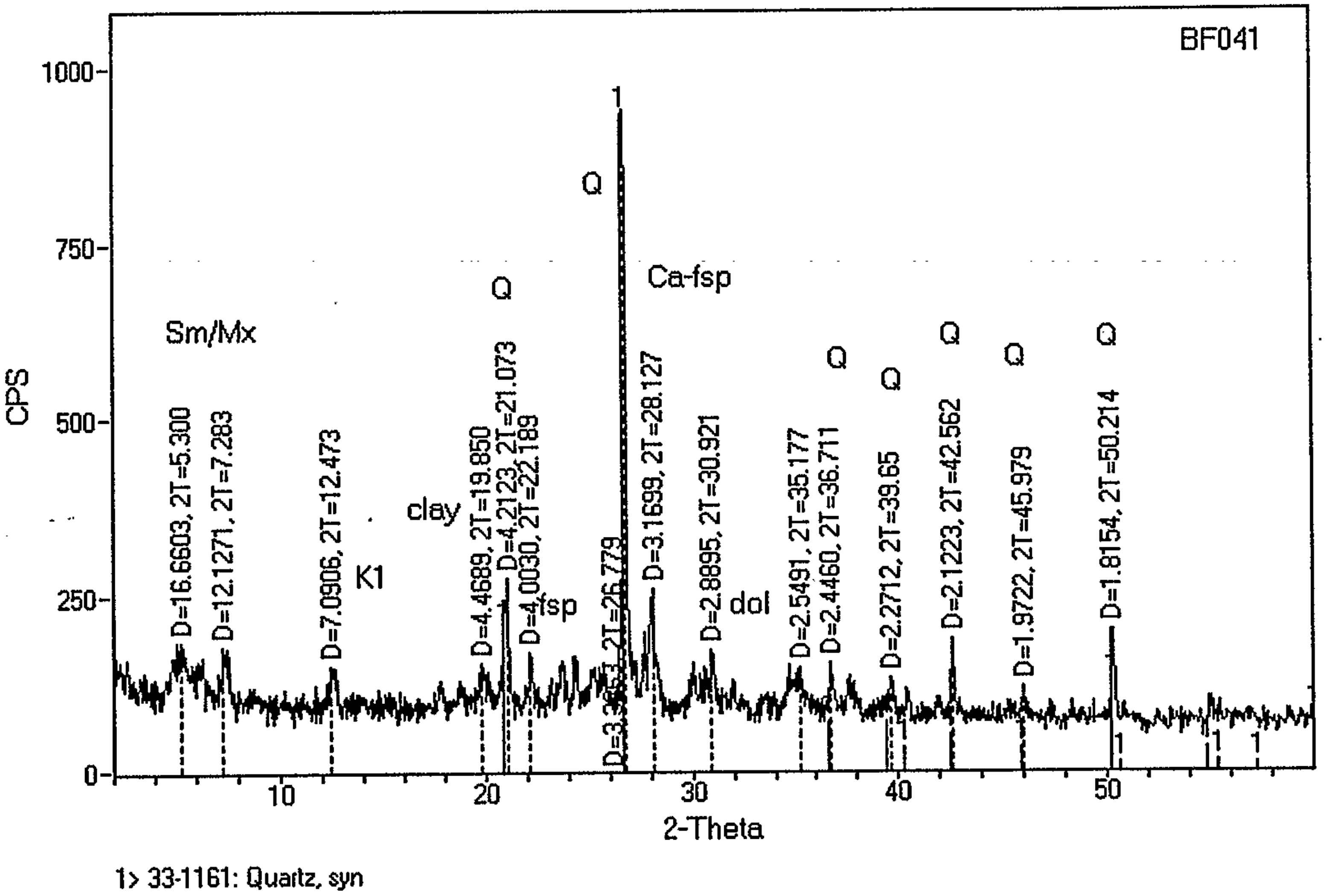


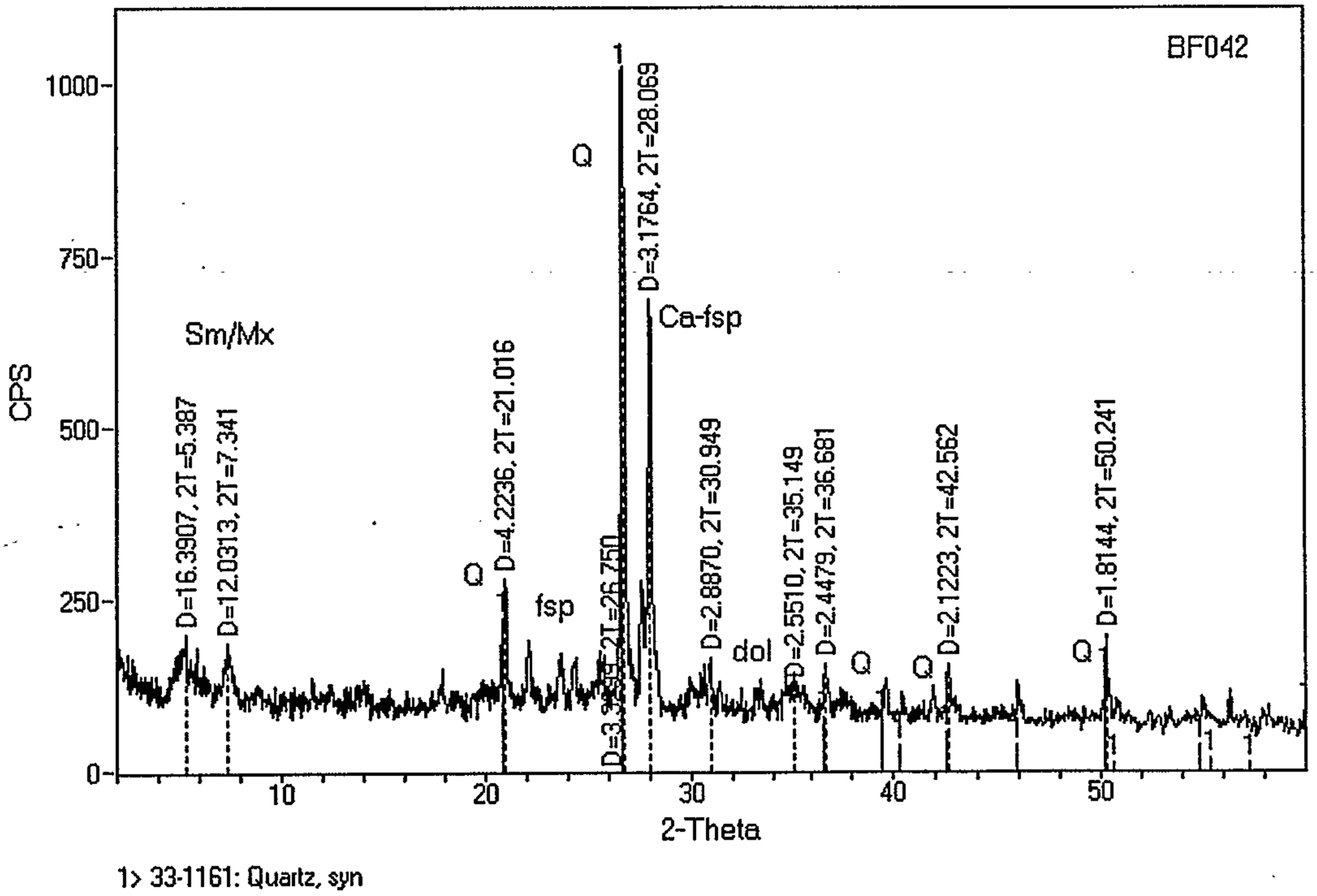
1> 33-1161: Quartz, syn

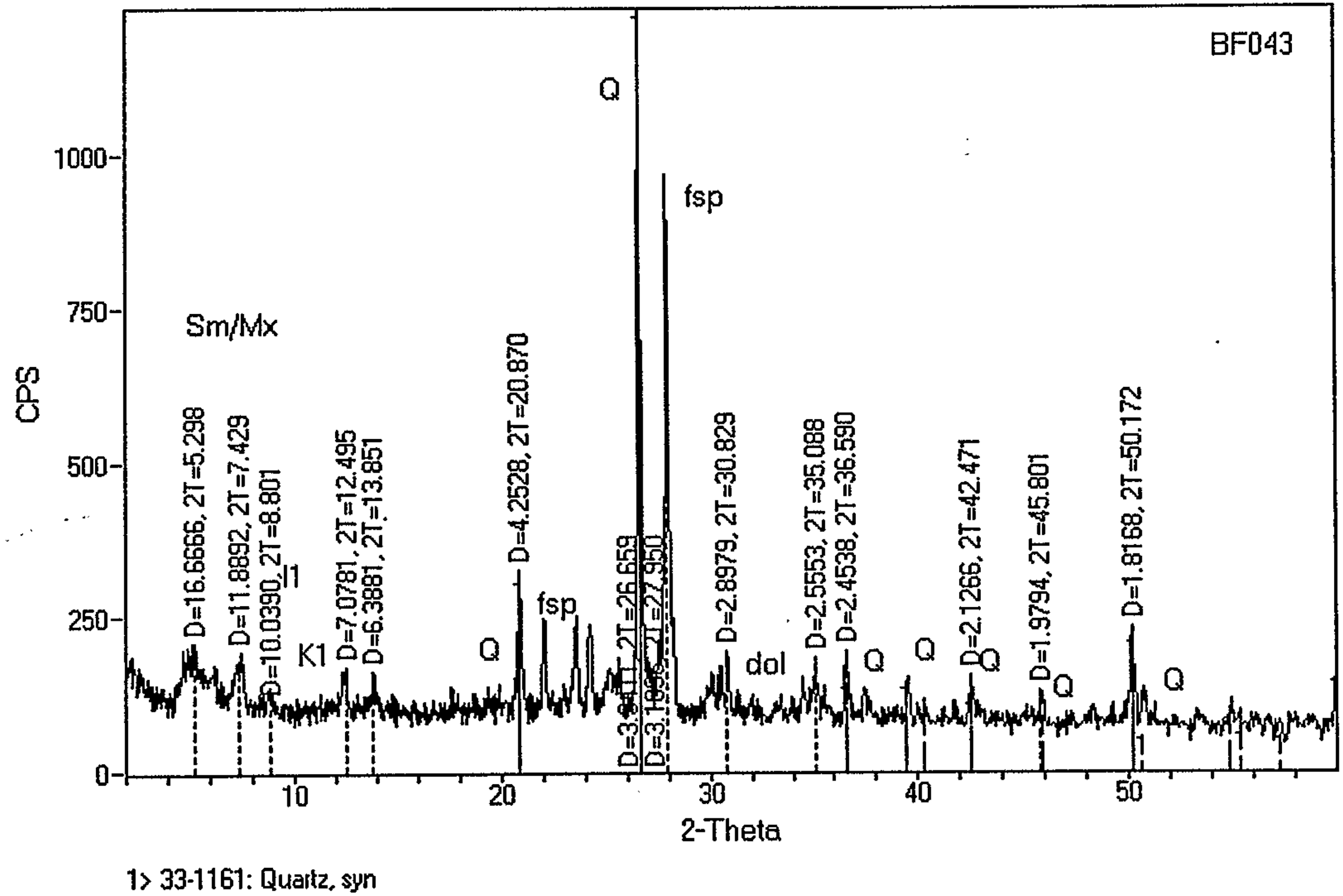


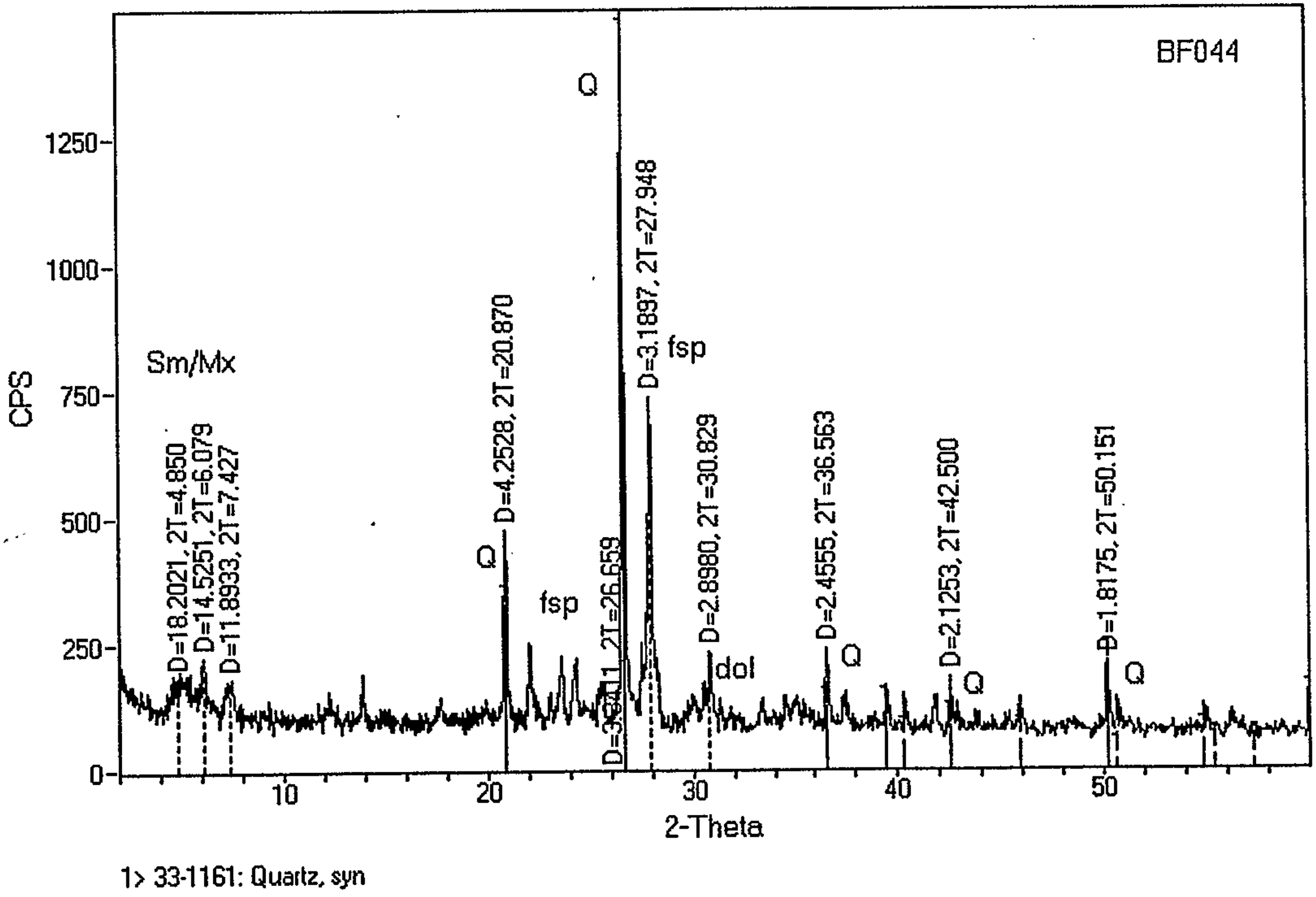
1> 33-1161: Quartz, syn

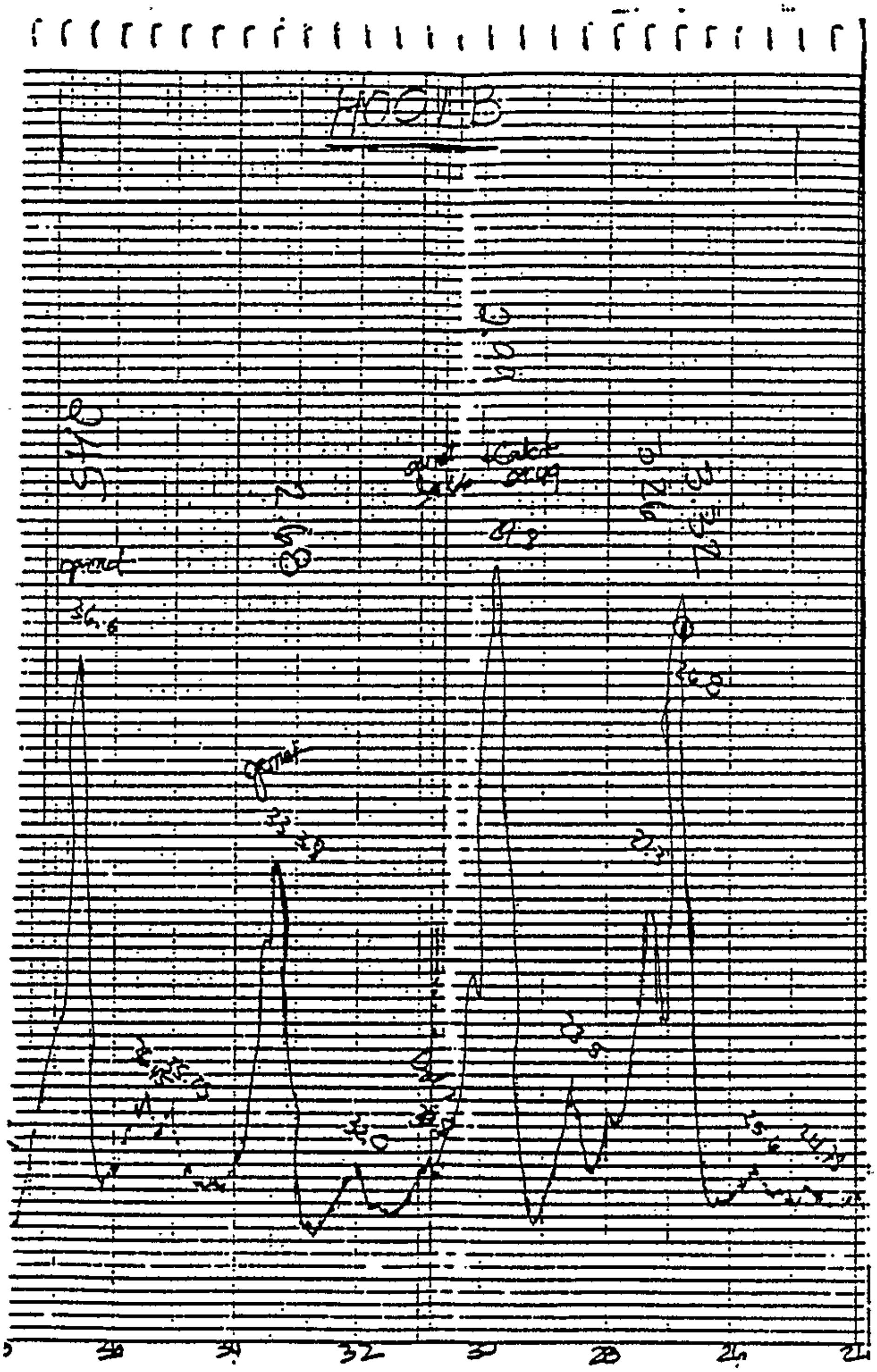

BF040
CPS
1500
1000
500
0
2-Theta
10
20
30
40
50
Sm/Mx
clay
Q
I1
K1
I2
K2
D=17.2437, 2T=5.120
D=11.8895, 2T=7.429
D=10.0281, 2T=8.810
D=7.1279, 2T=12.407
D=4.9922, 2T=17.752
D=4.4552, 2T=19.912
D=4.2290, 2T=20.989
D=3.5673, 2T=24.94
D=3.3299, 2T=26.750
D=2.5572, 2T=35.062
D=2.4480, 2T=36.681
D=2.1224, 2T=42.559
D=1.9746, 2T=45.920
D=1.8134, 2T=50.271
1> 33-1161: Quartz, syn

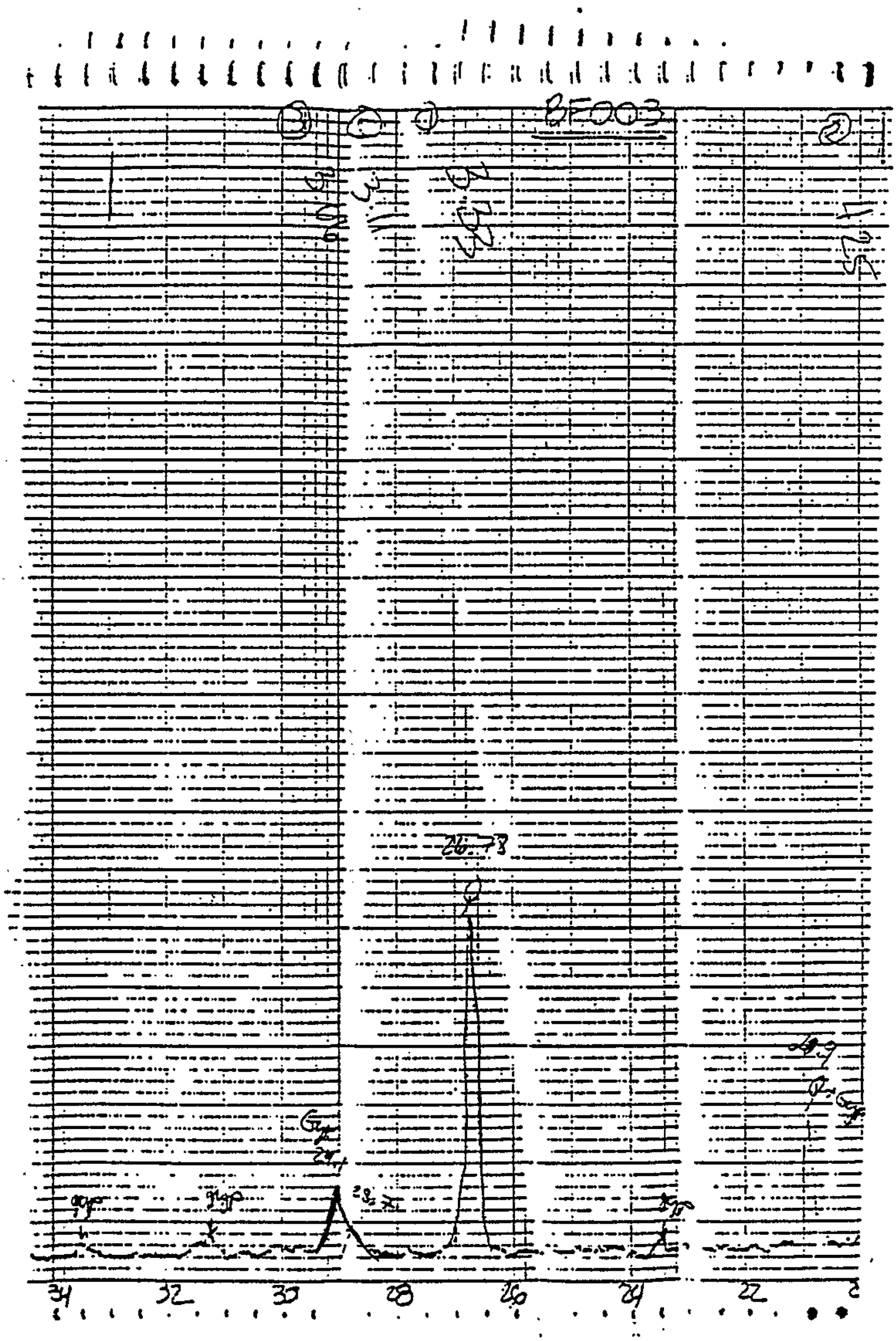

BF041
CPS
1000
750
500
250
0
10
20
30
40
50
2-Theta
Sm/Mx
K1
clay
Q
fsp
Q
Ca-fsp
dol
Q
Q
Q
Q
Q
1
D=16.6603, 2T=5.300
D=12.1271, 2T=7.283
D=7.0906, 2T=12.473
D=4.4689, 2T=19.850
D=4.2123, 2T=21.073
D=4.0030, 2T=22.189
D=3.3263, 2T=26.779
D=3.1699, 2T=28.127
D=2.8895, 2T=30.921
D=2.5491, 2T=35.177
D=2.4460, 2T=36.711
D=2.2712, 2T=39.65
D=2.1223, 2T=42.562
D=1.9722, 2T=45.979
D=1.8154, 2T=50.214
1> 33-1161: Quartz, syn

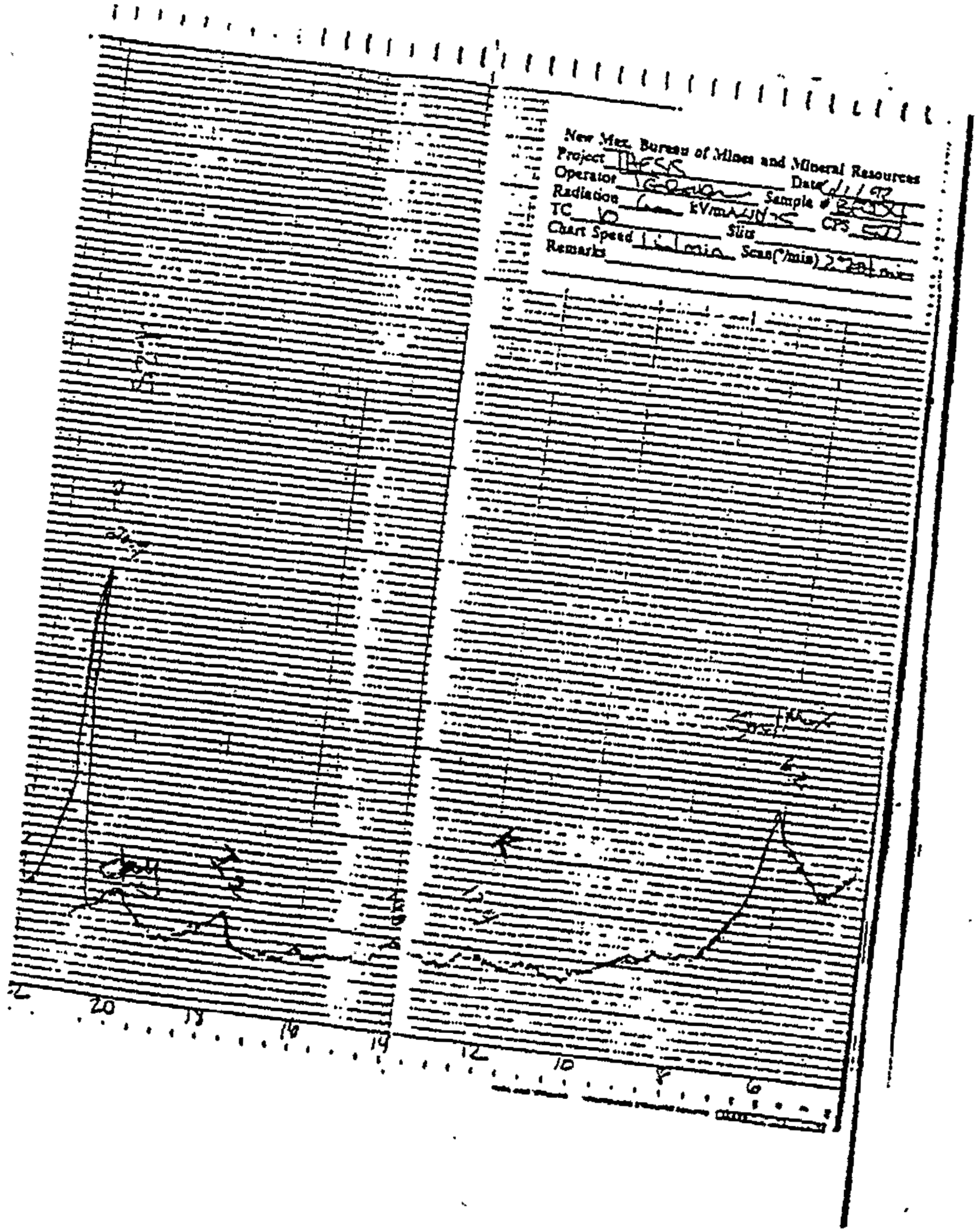

BF042
CPS
1000
750
500
250
0
10
20
30
40
50
2-Theta
Sm/Mx
D=16.3907, 2T=5.387
D=12.0313, 2T=7.341
Q
D=4.2236, 2T=21.016
fsp
Q
1
D=3.3
2T=26.750
D=3.1764, 2T=28.069
Ca-fsp
D=2.8870, 2T=30.949
dol
D=2.5510, 2T=35.149
D=2.4479, 2T=36.681
Q
Q
D=2.1223, 2T=42.562
Q
D=1.8144, 2T=50.241
1
1
1
1> 33-1161: Quartz, syn


BF043
Q
fsp
Sm/Mx
CPS
1000
750
500
250
0
D=16.6666, 2T=5.298
D=11.8892, 2T=7.429
D=10.0390, 2T=8.801
I1
K1
D=7.0781, 2T=12.495
D=6.3881, 2T=13.851
Q
D=4.2528, 2T=20.870
fsp
D=3.3411, 2T=26.659
D=3.1895, 2T=27.950
D=2.8979, 2T=30.829
dol
D=2.5553, 2T=35.088
D=2.4538, 2T=36.590
Q
Q
D=2.1266, 2T=42.471
Q
D=1.9794, 2T=45.801
Q
D=1.8168, 2T=50.172
Q
1
10
20
30
40
50
2-Theta
1> 33-1161: Quartz, syn

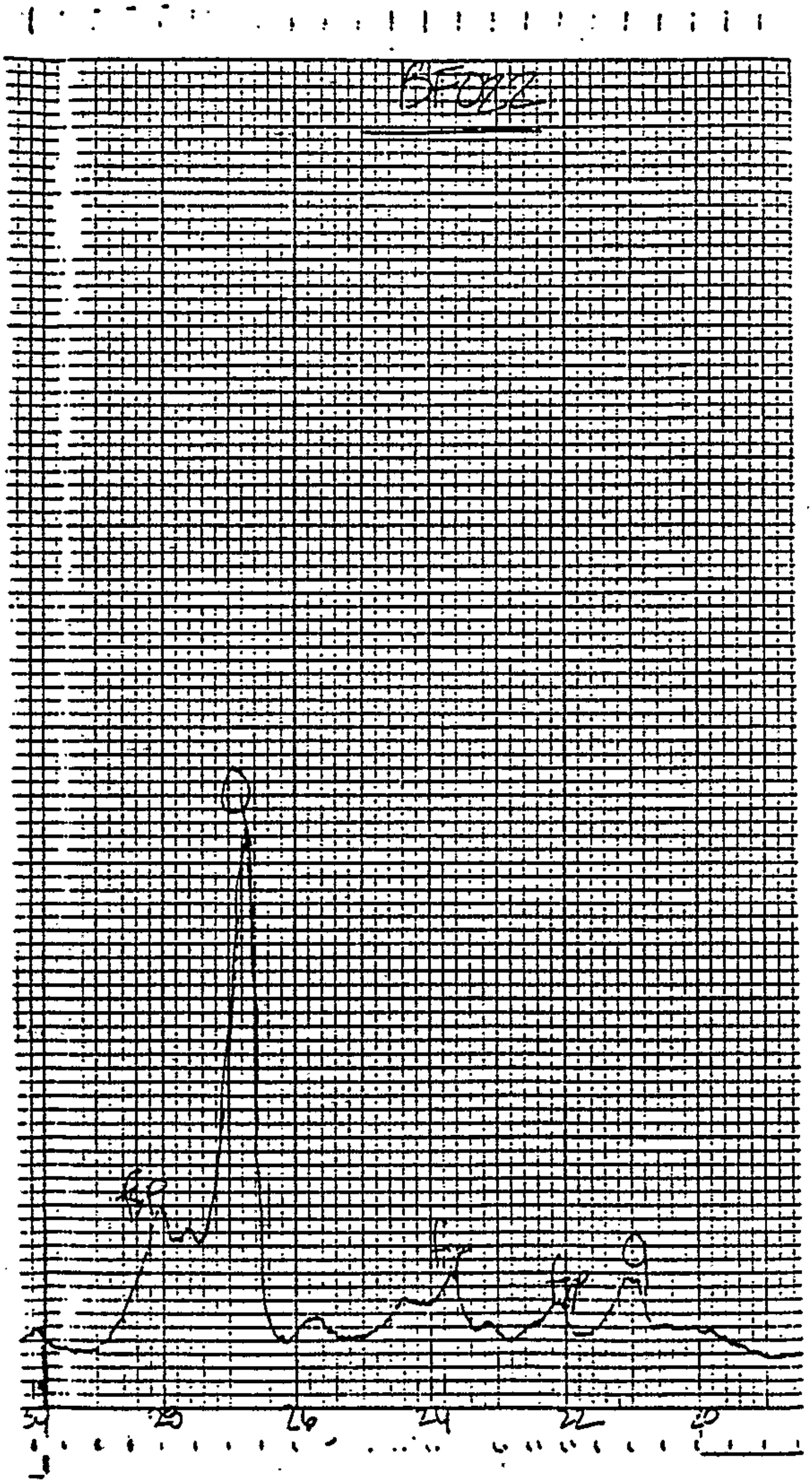

BF044
CPS
2-Theta
0
250
500
750
1000
1250
10
20
30
40
50
Sm/Mx
Q
fsp
dol
D=18.2021, 2T=4.850
D=14.5251, 2T=6.079
D=11.8933, 2T=7.427
D=4.2528, 2T=20.870
D=3.3411, 2T=26.659
D=3.1897, 2T=27.948
D=2.8980, 2T=30.829
D=2.4555, 2T=36.563
D=2.1253, 2T=42.500
D=1.8175, 2T=50.151
1
1> 33-1161: Quartz, syn


H09-LB
garnet
36.6
garnet
33.9
calcite
28.9
26.8
36
34
32
30
28
26
24


BF003
26.78
34
32
30
28
26
24
22
20



New Mex. Bureau of Mines and Mineral Resources
Project BESS
Operator [illegible] Date 6/1/92
Radiation Cu kV/mA 40/25 Sample # [illegible]
TC 10 CPS 500
Chart Speed 1 in/min Slits
Remarks Scan(°/min) 2°2θ/min


BF022
KP
Q
F
FP
Q
28
26
24
22
20

This thesis is accepted on behalf of the faculty of the Institute by the following committee:

Adviser

Andrew Campbell

Lynn Brandvold

May, 1993

Date