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A late-Quaternary record of environmental variability from lake sediment cores, Wind River Range, Wyoming

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A LATE-QUATERNARY RECORD OF ENVIRONMENTAL VARIABILITY FROM LAKE SEDIMENT CORES, WIND RIVER RANGE, WYOMING

An Abstract of a Thesis

Submitted

in Partial Fulfillment

of Requirements for the Degree

Master of Arts

Tyler John Johnson

University of Northern Iowa

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ABSTRACT

Sediment cores from two alpine lakes in Wyoming's Wind River Range were collected and analyzed to establish a record of depositional and mineralogical variability. Due to the hydrologic setting and isolation of Fiddlers and Louis lakes, these cores yielded the longest continuous limnological record in the region that extends back nearly 20,000 years to full-glacial conditions, a rarity for alpine lakes in the western United States.

To develop a paleolimnological record for Fiddlers and Louis lakes, the sediment cores were analyzed using four laboratory techniques. These techniques included particle size analysis, x-ray diffraction, heavy mineral analysis, and loss-on-ignition. Radiocarbon ages from Fiddlers Lake's sediment allowed the record of sedimentological changes to be numerically dated. Using this multi-proxy approach, a history of late-Quaternary depositional and mineralogical variability was established and compared with regional paleoclimate studies.

The results from the both lakes' cores showed similar responses to local and regional glacial/post-glacial environmental changes and revealed four distinct depositional phases: full-glacial, late-glacial, transitional and post-glacial. The timing of sedimentological responses in Fiddlers and Louis lakes corroborates previous research in the Wind River Range, most notably that of Fall, Zielinski and Davis (1995).

Paleoclimate records developed from this study enhance the present understanding of the region's climate history while the sedimentological data give insight into the depositional characteristics during climate transitions.

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Entitled: A late-Quaternary record of environmental variability from lake sediment cores, Wind River Range, Wyoming

has been approved as meeting the thesis requirement for the

Degree of Master of Arts

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TABLE OF CONTENTS

PAGE

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Reconstructions of paleoenvironmental changes in Wyoming's Wind River Range are presently limited to the past 14,000 years. The bulk of available information reflecting environmental changes comes from depositional features that were formed during or after glacial retreat (i.e. moraines or lakes impounded by moraines). Lack of evidence prior to deglaciation is due to few localities primed to record conditions or the destruction/erosion of then-existing records during glacial activity or retreat.

Previous paleoclimate studies of the Wind River Range have focused on outlining glacial sequences since the late Pleistocene or building a chronology of vegetative shifts during the Holocene. However, these studies contain records that extend only to the post-conditions; thus, little is known about environmental conditions during full-glacial time in the Wind River Range. In addition to the lack of full-glacial data, there has been little research on the response of sedimentological patterns during climate transitions.

To better understand sediment transport and accumulation during full-glacial, transitional, and post-glacial time, sediment cores were collected from two sub-alpine lakes in the southern Wind River Range. Through a multi-proxy approach, this study establishes a record of depositional and mineralogical variability in a lake setting as it relates to glacial and post-glacial conditions. The sedimentological characteristics of Fiddlers and Louis lakes provide a continuous record that documents paleoenvironmental conditions extending nearly 20,000 years into the past.

Paleolimnology

Paleolimnology is the study of past conditions and processes in lake basins and the interpretation of the histories of these systems (Last & Smol, 2001). Lakes respond physically, chemically and biologically to environmental changes and thus are excellent sensors to climate variations (Battarbee, 2000).

The local hydrologic and depositional settings greatly influence the ability of a lake to reflect local and regional paleoenvironmental conditions. As lakes are relatively small bodies of water, they are able to respond relatively quickly to changes in the environment (Cohen, 2003). Changes in the stratigraphic sequence of the lake deposit are used to infer changes in the environment over time (Anderson, Goudie, & Parker, 2007).

Depending on the nature of the depositional environment, lake studies have the ability to provide long term records of Earth's paleoclimatic history. These archives may offer high resolution records spanning long periods of time. Lake systems that are still active may provide more detailed records due to well-preserved paleoenvironmental indicators (Cohen, 2003).

When compared to oceans or other terrestrial sites, lakes are depositional environments with high sedimentation rates. Because of high accumulation rates, the minimum sampling interval, or resolution of lake cores has been found to be decadal or even annual (Bradley, 1999). The deposition of sediment in most lakes also proves to be relatively continuous which contributes to their usefulness as paleoclimatic records (Cohen, 2003). Continuous, millennia-long records with decadal or even seasonal resolution may be collected allowing paleolimnology studies to be directly linked to past climate (Woodhouse & Overpeck, 1998).

Accumulated sediment in lake systems include physical sedimentary inputs such as mineral, chemical, and biogenic sediments and may also contain cosmogenic or volcanic particles, fossils, or aerosol and waterborne pollutants (Cohen, 2003). Analysis of the sediment's physical properties may determine past depositional and paleoenvironmental conditions (Mazzuchi, Spooner, Gilbert, & Osborn, 2003). The accumulated sediments are the most important records in paleolimnological studies since they may last much longer than the lake itself or its geomorphology (Fritz, 1996).

Several proxies are needed from a lake system to provide a thorough representation of a lake's environmental history and to establish an accurate climatic hypothesis. Using laboratory techniques that study the physical, mineralogical, and geochemical indicators within the sediment, much information can be learned about the past environmental conditions within a lake's basin.

Purpose of Paleoclimatic Reconstructions

Reconstruction of past climate provides a longer perspective of climatic variability and offers insight to the causes and mechanisms of climatic change. Without paleoclimate research, the causes of climate change and natural environment processes cannot be fully comprehended. Furthermore, future variability can be predicted with more confidence when a detailed understanding of past effects is acquired (Bradley, 1999).

Paleoclimatology studies are undertaken to establish patterns of natural variability and to generate testable hypotheses concerning recent and future climatic changes (Fritz, 1996). Since past conditions or changes in climate cannot be observed, reconstruction of paleoclimate relies on the study of environmental responses that are climate-dependent to act as proxy records. Proxy records depend upon detailed observation of modern phenomena to infer past climate and climate fluctuations. Lake sediment cores are a valuable archive of proxy data and can be used to compare climatic change with patterns and rates of terrestrial response (Fritz, 1996).

This study establishes a paleolimnological record of environmental responses for the southern Wind River Range spanning approximately 20,000 years. The depositional settings of Fiddlers and Louis lakes reflect changes in the environmental conditions as they relate to climate and climatic transitions. Paleoclimate records developed from this study enhance the present understanding of the region's climate history while the sedimentological data give insight into the depositional characteristics during climate transitions.

Analyses Used in this Study

To develop a paleolimnological record for Fiddlers and Louis lakes, the sediment cores were analyzed using four laboratory techniques. These techniques included particle size analysis, x-ray diffraction, heavy mineral analysis, and organic matter content.

Particle size analysis determines the size distribution of the sampled sediment and may offer an indication of the source of the particles, mechanisms responsible for transport, and paleoclimatic conditions within the surrounding watershed (Last, 2001).

Performing particle size analyses on sediment cores reveal trends or variations in the sediment relating to the environmental settings during deposition.

X-ray diffraction assesses the mineralogical make-up of the sediment. Mineralogical investigations reflect the nature and intensity of weathering processes in the watershed and the origin of the sediments (Cohen, 2003). Presence of minerals foreign to the local basin may indicate fluctuations in the climatic regime of the watershed.

Heavy mineral identification indicates origin of mineral sediments. Quantitative data derived from identification of heavy, non-native volcanic minerals in Wind River Range soils illustrated significant eolian processes have been active throughout glacial and post-glacial time (Dahms, 1993). The presence of non-native heavy minerals can indicate variations in environmental conditions that cause predominant transport mechanisms to change over time.

Organic matter content is measured by performing a loss-on-ignition (LOI) analysis. LOI serves as a proxy of biologic productivity within both the lake and its basin (Corbett & Munroe, 2010) and can be useful for indicating periods of low glacial activity (Zielinski & Davis, 1987).

Magnetic data and radiocarbon ages from the sediment cores were provided by Christoph Geiss (personal communication, February 15, 2010). Past fluctuations in the production of atmospheric ^{14}C result in differences between calendar ages and radiocarbon ages (Bjorck & Wohlfarth, 2001). Therefore, ages obtained by radiocarbon dating are commonly calibrated to ensure agreement and accuracy. Dates contained in this study have been calibrated using CALIB 6.0.1 (Stuvier & Reimer, 2010) or interpolated from IntCal09 data (Reimer et al., 2009). Dates are recorded as calibrated years before present (cal. years BP).

Magnetic susceptibility data serve as proxies of minerogenic contribution (Zolitschka, Mingram, Gaast, Jansen, & Naumann, 2001) and can be used to discern periods of glacial activity from interglacials (Geiss, Dorale, & Dahms, 2007; 2009). Paleomagnetic data allowed correlation between Fiddlers and Louis lake cores.

Study Area

Fiddlers Lake and Louis Lake are located within the Little Popo Agie drainage basin in west-central Wyoming (Figure 1). These lake basins are approximately twenty miles southwest of Lander, Wyoming in the southeastern Wind River Range. The lakes are approximately two and a half miles apart and occupy small sub-basins on opposite sides of the Little Popo Agie Valley (Figure 2).

The lakes are situated in the montane forest zone of the southeastern Wind River Range at elevations of 9,400 feet (Fiddlers Lake) and 8,600 feet (Louis Lake). Land cover within both basins is predominately evergreen forest (U.S. Geological Survey, 2003). Shrubland, deciduous forest and pasture are present as well; the basin of Louis Lake also contains patches of grassland.

Fiddlers Lake has an area of approximately 50 acres, while Louis Lake's area is 114 acres. The drainage basin areas of Fiddlers and Louis lakes are approximately 397 acres and 5,350 acres, respectively. The drainage basin to lake area ratios are 8:1 (Fiddlers Lake) and 47:1 (Louis Lake).

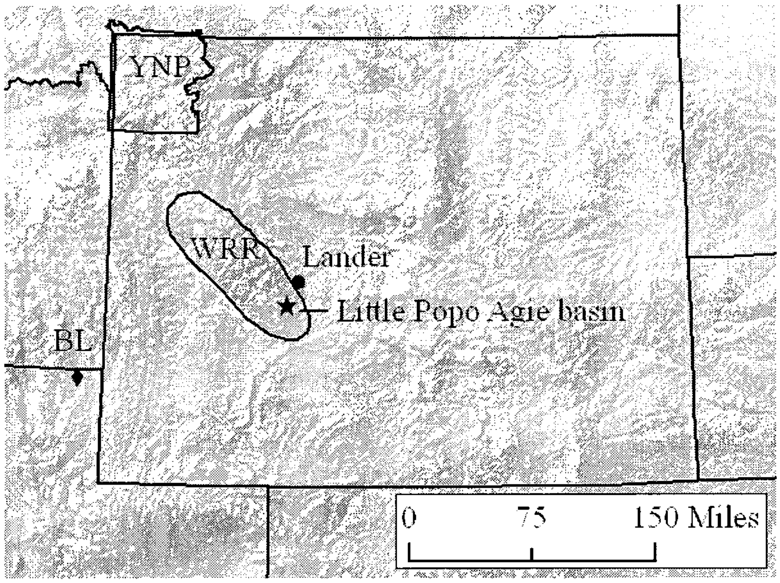


Figure 1: General location map of Little Popo Agie Basin within the state of Wyoming. Also shown are Lander, the Wind River Range (WRR), Yellowstone National Park (YNP), and Bear Lake (BL). Modified from USGS data (http://seamless.usgs.gov/).

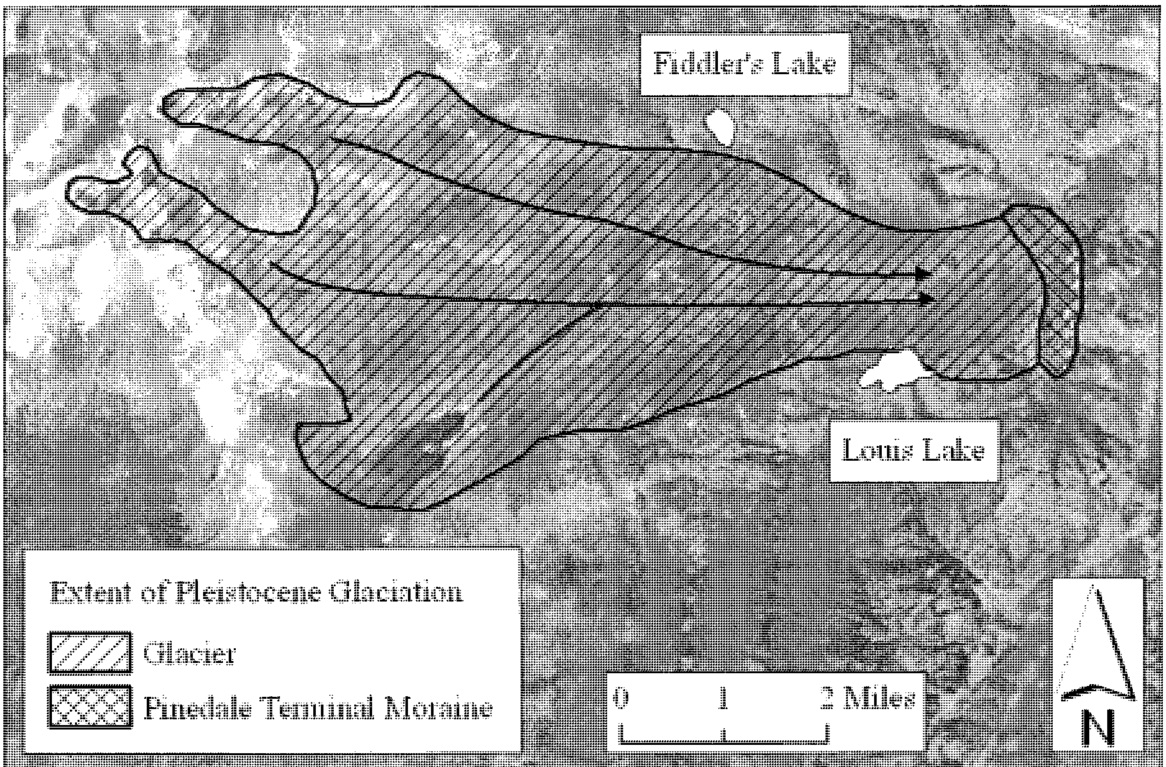


Figure 2: Fiddlers and Louis lakes and extent of Pinedale glaciation. Modified from USGS (http://seamless.usgs.gov/) and WyGISC (http://www.uwyo.edu/wygisc/) data.

Surficial geology surrounding both lakes is made up of bedrock outcrops and/or residuum mixed with alluvium, colluvium, eolian deposits, and grus (Case, Arneson, & Hallbe, 1998). The bedrock underlying both basins is the granodiorite of the Louis Lake Pluton. This formation is composed of biotite- and hornblende-bearing granitic rocks (Frost, Frost, Hulsebosch, & Swapp, 2000).

The Wind River Range exhibits distinct vegetation zones caused by a steep climatic gradient which respond well to environmental changes (Fall, Davis, & Zielinski, 1995). Also, the position and height of the mountain range allows it to lie between two climatic regimes as it is influenced by local summer storms as well as winter storms from the Pacific. Based on relative-age dating of glacial deposits in the Wind River Range, Dahms (2002) concluded that climate variability had been relatively synchronous in the region since glacial time.

Importance of Study Area

Reconstructing climate during a glacial/interglacial transition is important as it provides insight relevant to understanding glacial terminations (Anderson et al., 2007). Throughout the Rocky Mountain region, studies of alpine lakes provide abundant data on paleoenvironmental conditions during much of the Holocene (A. Noren, personal communication, December 18, 2009). Less is known about conditions prior to Holocene warming and deglaciation. There have been no paleolimnological studies of lakes containing full-glacial depositional records in the region.

The importance of Fiddlers Lake and Louis Lake to the environmental record of the Wind River Range results from their hydrologic isolation. During the Pinedale and

Bull Lake episodes of Pleistocene glaciation, both lake basins were dammed by the lateral moraines of advancing alpine glaciers in the Little Popo Agie Valley (Figure 2). This damming caused each basin to be isolated from any input or erosion from the larger, glacier-fed alpine drainage system. There may have been a small glacier in Louis Lake's headwaters during full-glacial time, though it would not have extended to Louis Lake's basin. At present the lakes only hydrologic inputs are from summer rainfall, winter snowpack runoff, and local groundwater input in each basin.

During full-glacial conditions, the Little Popo Agie Valley's equilibrium line altitude (ELA) was estimated to be approximately 9,620 feet using the toe-to-headwall ratio method (D. Dahms, personal communication, February 1, 2010). This apparently placed the Fiddlers and Louis lake basins just below upper tree line. The position of both lakes near the climatically-sensitive tree line allowed rapid responses to variations in the local environment.

The proximity of Fiddlers and Louis lakes to one another allows data from both lakes to corroborate spatial and temporal information about past hydrologic and limnological changes and variability. Preliminary results from magnetic variability and radiocarbon age data have shown the Fiddlers and Louis lake sediment records can be correlated to regional paleoenvironmental conditions (Geiss et al., 2007; 2009).

Since the Fiddlers and Louis lake basins were not occupied by ice during the late Pleistocene, the sediments contain a more complete (longer) sediment record than other lakes studied in the region. Previous studies of lake sediments in the Wind River Range have documented paleoenvironmental conditions but the records are limited to post-glacial sediment since those lakes now occupy cirque basins that were filled with ice during glacial advances (Fall et al., 1995; Gosse et al., 1999; Zielinski, 1989; Zielinski & Davis, 1987). In contrast, Fiddlers and Louis lakes provide an undisturbed and continuous full-glacial sediment record reaching back to almost 20,000 years before present (BP). Consequently, these lakes offer a unique, high-resolution record of a glacial to post-glacial transition, as well as full-glacial and Holocene environmental conditions in the region.

Research Questions

Based on the methods, results and interpretations of previous paleolimnological research, I pose the following research questions:

What are the depositional and mineralogical characteristics of the sediment?

What overall patterns or trends are displayed in the results?

Do the lakes provide corroborative evidence for regional climate variations?

CHAPTER 2

LITERATURE REVIEW

Regional networks of paleolimnological sites have the potential to corroborate variations in climate change (Battarbee, 2000). Along with the wide distribution of lakes, the greater temporal and spatial resolution provided by lake sediment has the potential to develop continental-scale paleorecords of climate change (Schnurrenberger, Russell, & Kelts, 2003).

Study sites are chosen based on their ability to preserve paleoenvironmental indicators and their sensitivity to climatic shifts. Contemporary studies of lake sediments often use multiple lines of proxy evidence to thoroughly reconstruct past climate. While some studies analyze sediment from one lake, multi-proxy analysis from multiple sites is necessary to provide an effective paleoclimatic reconstruction (Battarbee, 2000).

Climate history is inferred using paleoclimatic proxies and indicators. The validity of a region's climate history is strengthened when multiple study sites confirm interpretations. Therefore, independent studies seeking to reconstruct paleoclimatic changes use similar proxies or dating methods in an attempt to corroborate results.

Beyond simply reconstructing climate histories, paleolimnological studies can chronicle changes in sedimentation sources and mechanisms (Dean et al., 2006), constrain ages of geomorphic features (Macleod, Osborn, & Spooner, 2006; Zielinski, 1989; Zielinski & Davis, 1987), identify episodes of glacial activity (Armour, Fawcett, & Geissman, 2002), track changes in tree line position (Fall et al., 1995; Legg & Baker, 1980; Reasoner & Jodry, 2000), record variations and frequencies of forest fires (Millspaugh, Whitlock, & Bartlein, 2000), and outline ecological changes (Lynch, 1998; Whitlock & Bartlein, 1993).

Late Quaternary Paleolimnology

Rocky Mountain Sites

In most studies from alpine lakes in the Rocky Mountains, investigators use both biogenic and physical analyses to document environmental changes. Grain-size distributions, paleomagnetic values, and organic matter contents of lake sediment are commonly examined while pollen and charcoal studies are conducted where data are available. Comprehensive results from multiproxy analysis allow detailed paleoenvironmental variations to be documented.

Accumulated sediment from Otokomi Lake in Glacier National Park was analyzed to determine the age of a nearby moraine (Macleod et al., 2006). A core chronology was determined from examining tephra (volcanic ash) stratigraphy and comparing to known ash deposit dates. While numeric dating of sediment was not performed, relative-age dates were provided by analyzing the mineralogy of ash layers. Diagnostic mineral assemblages allowed tephra in the Otokomi Lake sediment to be correlated to ash layers with numeric ages in other lake studies. The relative-age dating of the sediment's ash layers constrains moraine formation due to colder conditions within the Younger Dryas interval (approximately 12,900-11,700 cal. years BP).

Multiple analyses including loss-on-ignition, grain-size distributions, and magnetic susceptibility were examined to infer paleoclimatic changes associated with glacial activity. Evidence for moraine deposition was marked by a correlative shift in the multi-proxy data, most notably by the coarsening of sediment deposited.

Several sediment cores from alpine lakes and bogs in Windsor Creek basin in Northern New Mexico were examined to identify episodes of glacial activity during the late Quaternary (Armour et al., 2002). By analyzing the geochemical properties and sedimentology of the cores, past hydrologic changes in the basin were revealed. Numeric ages of climate transitions provided by radiocarbon dating allowed researchers to correlate local climate changes with hemispheric cold events in the central Rockies and basins to the west (Armour et al., 2002).

Radiocarbon dating provided a minimum age for Pinedale deglaciation for Windsor Creek basin at approximately 13,900 cal. years BP (Armour et al., 2002). In response to warmer climate following deglaciation, organic sedimentation increased. A period of glacial advance was marked by an increase in magnetic susceptibility (MS), decreases in organic material, and coarser sediment deposition. Radiocarbon dates constrained this cold event and correlated changes at this site just after termination of the Younger Dryas interval approximately 11,300 cal. years BP. Four subsequent episodes of colder climate during the middle to late Holocene were inferred by coarser sediment, MS spikes and decreases in organic carbon content. Distinct changes in sediment texture and organic matter content from the multiple lake cores showed consistent responses to changes in precipitation and climate.

Along Colorado's Front Range, changes in climate and tree line position have been documented using pollen records from sediment sampled from Devlins Park (Legg

& Baker, 1980). Similar to Fiddlers and Louis lakes, the basin of Devlins Park was dammed by ice during Pinedale glaciation and the accumulated sediment preserved a record vegetation conditions during full-glacial time.

The emplacement of a moraine initiated sedimentation at Devlins Park and organic material from the base of the sediment was dated at approximately 26,400 cal. years BP (Legg & Baker, 1980). A radiocarbon date from the uppermost lake sediment was 14,200 cal. years BP, which represents the retreat of Pinedale glaciation and subsequent draining of the lake. Sediment samples yielded fossil pollen grains which were identified to classify paleoclimatic conditions.

Past vegetation changes were interpreted by comparing the altitudinal changes of modern pollen species with the pollen concentrations found in the Devlins Park sediment. By determining the variation of past tree line elevation at the site and interpolating conditions of two climate stations nearby, Devlins Park was concluded to be cooler and wetter during Pinedale time (Legg & Baker, 1980).

High-resolution pollen records from two other high-elevation lakes in Colorado document timberline and vegetative changes that date back to the Younger Dryas interval approximately 12,900-11,700 cal. years BP (Reasoner & Jodry, 2000). Sky Pond is located in the Rockies' Front Range in north-central Colorado and Black Mountain Lake in southwestern Colorado lies in the San Juan Range. Both sites are situated near the temperature-sensitive tree line so responses to climate changes were well-documented in the sediment record.

The age of the sediment record was calculated using radiocarbon-dated macrofossils and humic acid ages. Changes in pollen accumulation rates and shifts in local and regional pollen species assemblages were found to be synchronous at both sites. Using modern pollen species and tree line elevation data as analogs, patterns of tree line migration in response to climate change were inferred.

According to pollen accumulation rates and shifts in the pollen assemblage, warmer conditions caused tree line to move upslope at approximately 13,600 cal. years BP. Around 13,000 cal. years BP, pollen accumulations and arboreal pollen species decrease indicating a cooling event. This cold episode dominated by shrub and herb species lasted until around 11,400 cal. years BP when arboreal species and pollen accumulations quickly increased.

The pollen data from both lakes show an immediate response to before and after a cooling event associated with the Younger Dryas interval (12,900-11,700 cal. years BP). The timing and vegetative responses found in this study are consistent with other studies in the region that propose cooling during the Younger Dryas interval.

In the northern Rocky Mountains' Bitterroot Range, a Holocene climate record was constructed based on charcoal and pollen analysis (Brunelle, Whitlock, Bartlein, & Kipfmueller, 2005). Cores were taken from four lakes and analyzed to corroborate vegetative and fire history of the region. The lakes are situated along a west-to-east gradient across the Bitterroot Range transect and presently have differing precipitation regimes (i.e. summer-dry or summer-wet regimes). Magnetic susceptibility values, organic matter content and radiocarbon ages were determined from the lakes' sediment. Fire frequency data were derived from charcoal accumulations.

Patterns of vegetation shift at the study sites were not synchronous though this was attributed to elevational gradients; similar climate transitions occurred between sites but lags were due to species migration up or down slope. Major climate transitions occurred at approximately 11,000 and 6,800 cal. years BP. Prior to 11,000 cal. years BP, conditions at all sites were colder than present. This was signified by pollen indicative of alpine vegetation and fire frequencies that are consistent with present-day alpine or subalpine environments. During the early Holocene interval (11,000-6,800 cal. years BP), present-day precipitation regimes were amplified; fire frequency data showed summer-dry sites experienced drier conditions while summer-wet sites were wetter. The presence of *Pseudotsuga* pollen at most sites also confirmed tree line was higher during the early Holocene as the *Pseudotsuga* species presently occupies lower elevations.

After 6,800 cal. years BP, conditions gradually stabilized to present conditions. Climatic conditions that were amplified during the early Holocene gradually diminished and present conditions and forest composition were established by about 3,000 cal. years BP. Multi-proxy evidence from lake sediments show that the timing of vegetation changes and fire events were caused by regional climate variations and were relatively synchronous when migration was taken into account.

<u>Northern Great Basin</u>

Bear Lake, which is situated in the Great Basin just west of Wyoming along the Idaho-Utah border (Figure 1), has been the focus of numerous paleolimnological studies

(Dean et al., 2006; Jimenez-Moreno, Anderson, & Fawcett, 2007). In the past, Bear Lake fluctuated between being a topographically closed basin during interglacials, to a topographically open basin during colder, wetter glacial periods which caused lake level to rise and allowed Bear Lake to be fed by Bear River. Although the hydrologic and geomorphic setting of Bear Lake is not analogous to Fiddlers and Louis lakes, its proximity provides the potential for corroborating the paleoclimatic reconstructions for the Wind River Range.

Three sediment cores from Bear Lake provided a composite record spanning the past 31,000 years (Dean et al., 2006). To examine glacial-to-Holocene changes in sedimentation characteristics, researchers relied on geochemical proxies from Bear Lake sediment to track environmental change. Along with sediment samples from along Bear River and within the lake catchment, the sediment cores provided evidence of changes in sediment source. Carbonate mineralogy was the dominant proxy used to record environmental change in Bear Lake. Measures of carbon and oxygen isotopes and the preferred form of carbonate precipitate (i.e. aragonite or calcite) determined the dominant source of hydrologic input to Bear Lake. Magnetic properties and organic carbon contents were also used as to corroborate changing environmental conditions (Dean et al., 2006).

During full-glacial time (prior to 18,000 cal. years BP), Bear Lake was fed by Bear River as evidenced by hematite-rich, detrital sediment. As air and water temperature and evaporation increased after 18,000 cal. years BP, calcite deposition and organic productivity increased as Bear River abandoned Bear Lake. By 12,000 cal. years BP, aragonite replaced calcite as the dominant carbonate as temperature and evaporation continued to increase, though groundwater input to Bear Lake remained significant (Dean et al., 2006).

A short-lived transition back to calcite formation at approximately 9,200 cal. years BP indicated greater freshwater input and a rise in lake level. Increased snowpack and snowmelt during a cool episode was concluded to be the cause of the reentry of Bear River into Bear Lake. After 8,200 cal. years BP, Bear River was disconnected from Bear Lake and aragonite began forming again as evaporation exceeded precipitation.

In 2007, Gonzalo Jimenez-Moreno and colleagues analyzed high-resolution pollen data recovered from Bear Lake sediment. Using a 120-meter long lake core, the researchers were able to chart vegetative changes spanning approximately 225,000 years (Jimenez-Moreno et al., 2007). Strong correlations were found between the pollen fluctuations from this core and isotope and carbonate abundance derived from previous lacustrine studies at Bear Lake.

Spectral analysis of the pollen categorized glacial and interglacial episodes based on the dominant vegetation. Warmer, drier conditions during the early Holocene (after approximately 12,000 cal. years BP) were indicated by higher pollen percentages of juniper, oak, and flowering plants, aragonite deposition and enriched oxygen and carbon isotopes (Jimenez-Moreno et al., 2007). Cooler, wetter episodes during late-Pleistocene (prior to 12,000 cal. years BP) were marked by spruce and herb pollen, low aragonite content, and more negative oxygen and carbon isotopes.

Comparing the continuous paleoclimate record from Bear Lake with marine isotope stages and the Greenland ice record revealed responses to global climate patterns in the pollen data. 22,000 and 100,000-year fluctuations present in the data were attributed to orbital cycles of climate. 5,000 to 6,000-year cycles were also observed in the pollen record confirming sub-orbital climatic cycles (Jimenez-Moreno et al., 2007).

Greater Yellowstone Region

In the greater Yellowstone region, no lake records are available for interpreting full-glacial environmental conditions. Paleoenvironmental studies in this region rely heavily on pollen and charcoal data to track climatic changes through the Holocene. The location and complex topography of this region results in a spatially variable ecology over the past 17,000 years. At present, the climate of the northern Yellowstone region is characterized by summer-wet conditions while the southern region receives greater precipitation during the winter.

Whitlock and Bartlein (1993) presented a model to explain past ecological changes based on reconstructed climate history, paleoclimate simulations, and knowledge of present-day climate controls and regimes. Following deglaciation approximately 17,000 cal. years BP, the entire Yellowstone region experienced a collective response to changing environmental conditions. Fossil pollen from multiple sites suggests the region was dominated by subalpine parkland and alpine tundra as glaciers retreated and conditions were cooler and drier than present. As temperature and moisture increased, subalpine forest gradually migrated to the region after 12,900 cal. years BP.

At approximately 10,700 cal. years BP, present-day climate boundaries were in place as the summer-wet/summer-dry regimes are reflected in the pollen data. Early Holocene data from about 10,200 to 5,700 cal. years BP distinguish summer-dry sites as dominated by *Pseudotsuga* and Douglas-fir species which at present grow in warmer, drier conditions. From 10,200 to 7,800 cal. years BP, summer-wet sites are characterized by juniper, birch, pine, and an absence of *Pseudotsuga*. This assemblage implies conditions that were wetter than present.

Climate regimes were weakened through the late Holocene as summer-wet sites became drier and summer-dry sites became less arid than earlier. Relating fossil-pollen data to present-day climatic analogs, it was concluded that vegetation changes in the Yellowstone region occurred at roughly the same time throughout the Holocene but varied with location. That is, past changes in climate were not uniform, but reflected variables such as seasonal solar cycles and local orographic influences (Whitlock & Bartlein, 1993).

Pollen data from Loon Lake sediment cores provide more evidence that precipitation regimes were amplified in the early Holocene (Whitlock, Bartlein, & Van Norman, 1995). Loon Lake presently experiences a summer-dry regime but is located near the boundary between the summer-wet and summer-dry climate regimes. Organic matter from the sediment cores was radiocarbon-dated to establish a chronology of climate variability.

Four unique pollen assemblage zones were identified and compared to modern pollen analogs to infer past vegetation and climate at Loon Lake. Prior to 12,500 cal.

years BP, conditions at Loon Lake supported spruce, juniper and various herbs following deglaciation. From 12,500 to 10,700 cal. years BP, subalpine species dominated as indicated by spruce, pine, fir, and aspen species. Between 10,700 and 6,300 cal. years BP, an increase in herbs and shrubs within the pine-dominated forest represented the driest Holocene conditions at Loon Lake. After 6,300 years BP, pine and fir species decreased as the forest became more closed.

Pollen stratigraphy revealed that while the boundary between climate regimes remained stationary, conditions were drier at Loon Lake in the early Holocene. The vegetation history of Loon Lake is evidence that precipitation regimes are constrained by location and topography in the Yellowstone region (Whitlock et al., 1995).

A sediment core taken from Cygnet Lake in Yellowstone National Park provided a high-resolution charcoal record that spanned approximately 14,000 years and correlated fire frequencies with climate change (Millspaugh et al., 2000). The data showed that while vegetation remained constant, the frequency of large fires was primarily the result of climate variations. Using radiocarbon dates and the presence of tephra layers, researchers were able to create an age model and calculate sedimentation rates for the cores. Charcoal particles were counted and constituted a record of fire history and variation.

At approximately 17,000 cal. years BP, cool humid conditions during the late-glacial period resulted in a fire frequency rate of four per thousand years. A gradual increase to six fires per thousand years until around 11,700 cal. years BP indicated warmer and drier conditions. Fire frequency reached fifteen per thousand years at approximately 9,900 cal. years BP which represented the driest Holocene conditions. After 9,900 cal. years BP, fire frequency decreased to the present rate of two fires per thousand years as conditions became cooler and effectively wetter (Millspaugh et al., 2000).

Millspaugh and colleagues (2002) found that fire frequency variations were closely related to insolation anomalies and changes in regional climate. The period of greatest fire frequency coincided with the early Holocene insolation maximum. Fire occurrence in the Yellowstone region was concluded to be a non-stationary process that varies with climate and long-term variations in summer drought (Millspaugh et al., 2000).

Wind River Range

In previous studies, climate reconstructions of the Wind River Range have relied heavily on geomorphology to constrain ages of glacial activity. Increasingly, studies are utilizing lake sediment cores to substantiate records of glacial activity or establish vegetation histories through environmental proxies.

Multiple paleoclimate proxies were used to identify Holocene climate transitions in the Titcomb Basin in the northern Wind River Range (Gosse et al., 1999). Organic matter from five lake cores provided radiocarbon dates. Using loss-on-ignition, pollen data, and cosmogenic ages of moraine boulders and bedrock surfaces, Gosse and colleagues (1999) outlined a climate history of the basin following deglaciation.

Prior to about 15,900 cal. years BP, glaciers began to retreat exposing bedrock surfaces and paternoster lake divides. Sediment deposited in the newly formed Lower Titcomb Lake during this time was characterized by low organic matter content and low pollen concentrations. A standstill or re-advance of the valley glacier deposited the Titcomb Lake moraines that were dated at 11,400 and 11,700 cal. years BP. This moraine deposition coincides with the ending of the Younger-Dryas interval (12,900-11,700 cal. years BP). Ice retreat after 11,400 cal. years BP caused Upper Titcomb Lake to form behind the Titcomb Lake moraines. At approximately 11,400 cal. years BP, a shift to more organic sediment represented warmer conditions that persisted until around 5,100 cal. years BP. After this time, organic matter content declines as conditions become cooler.

By analyzing sediments from three lakes in the Wind River Range's Temple Lake Valley, the age of the type Temple Lake moraine was challenged by Zielinski and Davis (1987) using radiocarbon dates from sediment cores. The age of the type Temple Lake moraine is significant as it is the type locality for Younger Dryas glacial deposits found in the middle Rocky Mountain region. Temple Lake Valley is approximately fifteen miles northeast from Fiddlers and Louis lakes.

Sediment cores from Rapid, Miller and Temple lakes provided the proxies and data to reconstruct glacial activity of the valley during the Holocene. Organic matter content proved valuable as Zielinski and Davis (1987) concluded the abundance of organics changes inversely with glacial activity. Periods of low glacier activity (i.e. warmer temperatures) resulted in sediment deposits with higher organic material. Radiocarbon dates of organic material in the cores allowed researchers to constrain ages of glacial retreat and moraine deposition.

Basal sediment from Rapid and Temple lakes constrained the age of Temple Lake moraine deposition to approximately 13,900 cal. years BP. Organic matter content from Rapid and Miller lakes reached maximum values during early Holocene (8,300-10,000 years BP) representing warmer conditions. The basal dates and organic matter analysis interpreted by Zielinski and Davis (1987) refute earlier studies suggesting moraine deposition during the early Holocene. Previous research concerning the moraine age was conflicting due to the absence of valid dating techniques.

Later, Zielinski (1989) concluded that relative-age dating of geomorphic features may be problematic without corroborative proxies. Specifically, continuous records from lake sediments offer more reliable chronologies when used in conjunction with geomorphic analyses. Zielinski (1989) evaluated the accuracy of relative-age dating of rock glaciers by examining sedimentological data from the previous Temple Lake Valley sediment cores.

Grain-size analysis, loss-on-ignition, and magnetic susceptibility were examined, and radiocarbon dates provided numerical ages. Physical characteristics of the sediment such as absence of coarse material and stability of organic matter content suggested there was no convincing evidence of rock glacier activity in the past 12,000 years.

The ability to assign numeric ages from radiocarbon dating allowed Zielinski (1989) to establish a precise record of sedimentation characteristics that did not include active glaciation during the Holocene. Earlier studies asserting the Neoglacial timing (5,700-3,200 cal. years BP) of rock glacier activity were found to be inconsistent due to the lack of age constraints. When used in conjunction with relative-age chronologies, the dating and analysis of sediment cores lend more reliable results.

Building on the above work in the Temple Lake Valley, Patricia Fall and colleagues (1995) analyzed pollen from Rapid Lake's sediments to infer associated paleoclimate changes. Objectives were to reconstruct the vegetative history and past tree line elevation to develop a continuous paleoclimatic record of the southern Wind River Range (Fall et al., 1995). Pollen identification and counts were collected and sedimentological data from Zielinski (1989) and Zielinski and Davis (1987) were integrated to document the glacial and vegetation history of the Temple Lake Valley.

Based on radiocarbon ages, shifts in vegetation were numerically dated. Three distinct zones of pollen assemblages were identified. Prior to about 13,200 cal. years BP, pollen input was low and dominated by herb and shrub species. Conditions were analogous to present-day alpine tundra. Between 13,200 and 3,200 cal. years BP, pollen influx increases and is characterized by arboreal species. The environment during this time was interpreted to be a mixed conifer forest composed predominantly of pine with spruce and fir. Tree line was inferred to be 150 meters above its present position from early to middle Holocene. After 3,200 cal. years BP, the mixed conifer forest retreated to its present position as evidenced by a decline in subalpine conifer pollen. Modern vegetation composition characterized as white bark pine parkland was established at this time.

The data provided a history of both glacial and vegetative changes in the Temple Lake Valley. From the Rapid Lake data, Fall et al. (1995) constructed a detailed paleoclimatic record that exhibited warm conditions throughout the Holocene with maximum warmth and aridity in the middle Holocene (approximately 6,200 cal. years BP).

To test a hypothesis on the occurrence and origin of park vegetation in the northern Wind River Range's Fish Creek Park, fossil pollen data from multiple lake cores was used to reconstruct a history of Holocene vegetation (Lynch, 1998). Pollen identification was the primary proxy used for determining paleoclimatic trends, though loss-on-ignition analysis was also performed to determine organic matter content. Timing of environmental changes during the past 10,600 years BP was constrained by radiocarbon dating.

Pollen data prior to 10,700 cal. years BP indicates a tundra environment, as total pollen amount is less than modern tundra environments in the Wind River Range and is dominated by pine species. Organic matter content from this period is relatively low. From approximately 10,700 to 9,500 cal. years BP, a transitional phase is characterized by the establishment of parkland composed of pine, spruce and fir and increasing organic matter content.

Between 9,500 and 5,700 cal. years BP, an environment consisting of open parkland with isolated pine stands was indicated by pollen percentages dominated by pine with a notable grass component. After 5,700 cal. years BP, conditions became cooler and wetter suggested by a forest composed of spruce, pine, and fir. Park vegetation was established at three of the five study sites between 2,500 and 1,500 cal. years BP (Lynch, 1998). Though the cause was not known, the timing of park vegetation establishment coincides with regional cooling documented in other Wind River Range studies including Fall et al. (1995).

Little Popo Agie Basin

Presently, there has been no previous research reconstructing local paleoclimate within the Little Popo Agie River watershed. The location and hydrology of the lakes presents a unique setting adapted to record responses to environmental conditions. With the information gained from this study, paleoenvironmental variations within the Little Popo Agie Valley can be correlated to regional studies of Holocene climate variability in the Wind River Range.

The Fiddlers and Louis cores provide an uninterrupted sequence of paleoclimatic conditions dating back to the late Pleistocene. Radiocarbon dates and varve thickness measurements suggest the earliest sediments were deposited as early as 20,000 cal. years BP. Both lakes contain records of a full-glacial environment during the late Pleistocene, followed by a transitional response to deglaciation, to the arrival of full post-glacial conditions through the Holocene.

To produce a comprehensive history of environmental variability for the Fiddlers and Louis lake cores, analysis of multiple proxies was necessary. Sediment collected from the same Fiddlers Lake core analyzed in this study allowed Geiss and colleagues (2007; 2009) to conduct radiocarbon dating which provided numeric ages of paleoenvironmental changes recorded in the sediment. Paleomagnetic analyses yielded magnetic inclination and declination data which correlated the two sediment records (Geiss et al., 2007; 2009).

Together with Geiss' results, the paleolimnological data obtained from this study develops a record of sedimentological characteristics and patterns that contribute to the long-term record of environmental variability for the southern Wind River Range, Wyoming. Patterns of deposition and mineralogical characteristics of the sediment indicate transport and accumulation cycles. Analysis of the textural and organic properties determines regional precipitation variations. Results of this research comprise the longest continuous sediment record to come out of the Wind River Range.

CHAPTER 3

METHODOLOGY

Core Retrieval

In February 2004, four cores were collected from Fiddlers and Louis Lakes. Cores were retrieved by Dennis Dahms (University of Northern Iowa, Cedar Falls, IA), Christoph Geiss (Trinity College, Hartford, CT), and Jeff Dorale (University of Iowa, Iowa City, IA). A Livingstone 3.5 inch piston-corer was used to collect the sediment cores. Two cores taken approximately ten meters apart were collected from each lake and complete cores were eight-to-ten meters long.

The cores are stored at the LacCore Repository at University of Minnesota's Limnological Research Center (LRC). At the LRC, the cores were split in half longitudinally; one half was used for sampling and analysis and the other for description and archival. Sediment density, electrical resistivity, and magnetic susceptibility data were acquired using a multisensor core logger and cores were photographed for documentation (Myrbo, 2005). Detailed core descriptions were performed by Dennis Dahms and LRC staff and reported the overall structure, texture, and composition of the sediment. Based on these sedimentological characteristics, lithostratigraphic units were delineated.

Sampling of Cores

Sampling methods were derived from the LacCore documents and procedures (Myrbo, 2004). Only one core from each lake was sampled for this study's analyses.

Post-glacial sediments were sampled from the cores at ten-centimeter intervals. Due to the homogeneity and massiveness of the glacial sediment, those samples were taken every twenty centimeters. Visual distinction between glacial and post-glacial sediment at the time of sampling was based on color, texture and organic content.

Samples were taken in one-centimeter thicknesses (e.g., 10-11 cm, 20-21 cm, etc.). Target sample volume was approximately three cubic centimeters. Sediment samples were placed in airtight, plastic Polycon containers for transport and refrigerated during storage.

Depth and volume data for each sample were recorded including any observations or notes concerning sediment features. The naming convention of samples used in this study consisted of lake name, core section, and the sample's top depth within section (e.g. Lou_1L_70).

Sixty-seven samples were retrieved from the Louis Lake core and sixty samples were taken from the Fiddlers Lake core. From the Louis Lake core, thirty samples were taken from the post-glacial sediment and thirty-seven from the glacial. From the Fiddlers Lake core, seventeen post-glacial samples and forty-three glacial samples were taken.

Due to the geology of study area and parent material of the lake sediment, samples were not thought to contain significant carbonates. To ensure this, a subset of samples from each core was tested with hydrochloric acid and observed. No reactions occurred which confirmed the absence of significant carbonate material.

Particle Size Analysis

Prior to the particle size analysis (PSA), samples were treated with 30% hydrogen peroxide solution to remove organic matter. Approximately one cubic centimeter of sediment was subsampled and transferred to a 100 mL beaker for analysis. The sediment was washed with the solution while on a hotplate until addition of more solution failed to cause further reaction. Samples were air-dried and gently disaggregated.

A Beckman-Coulter LS 13 320 Laser Diffraction Particle Size Analyzer and associated software were used to obtain particle size measurements. The Aqueous Liquid Module (ALM) of the Beckman-Coulter was used for these analyses. Before each run, ten milliliters of hexametaphosphate was added to the ALM to act as a dispersant (J. Mason, personal communication, February 21, 2008). The dry sample was incrementally added to the ALM until desired obscuration was reached. Ideal obscuration was between nine and twelve percent.

A sonicator was used at power five during loading and measurement. Samples were run for sixty seconds and used the Fraunhofer optical model to compute sizes. The ALM was then drained, rinsed, and refilled before the next sample analysis. Each sample was run twice and the data averaged.

The various grain-size percentages were calculated using the LS 13320 software and the data were entered into a spreadsheet. Based on total volume percent for each sample, five grain-size fraction categories were created: sand (>50µm), total silt (2-50µm), medium/coarse silt (20-50µm), fine/very fine silt (2-20µm), and clay (<2µm).

Samples were plotted with SEDPLOT software (Poppe & Eliason, 2008) based on classification by Shepard (1954).

X-Ray Diffraction

Unused sample leftover from particle-size analysis was used for the X-ray diffraction procedure. Distilled water was added to the dry sample to create a slurry. Random-oriented mounts were prepared by applying slurry to an area of 3 cm^2 on a Coors porcelain tile and allowed to dry on a hotplate for twenty minutes. Samples were air-dried overnight before analysis.

X-ray diffraction was performed using a Rigaku MiniFlex Diffractometer with Cu K-alpha radiation and associated software. The standard scan using the Rigaku unit measured diffraction along a theta/2-theta scan axis. Diffraction was sampled every 0.03° with a scan speed of 2° 2-theta per minute. Scattering was set at 4.2° and divergence was set to variable. Intensity of the peak was measured in counts.

An initial air-dry scan was performed between 2° and 60° 2-theta on the untreated, air-dry sample to identify minerals in both silt and clay fractions. After the air-dry run, only the clay peaks were of interest, so all subsequent scans were limited to 2° to 30° 2-theta.

Starting with the second scan, samples were pretreated with a 0.5 M magnesium-chloride solution and allowed to air-dry overnight. Following the magnesium analysis, a glycerol solution was applied to the sample (1-2 drops) and the tile was placed in a glycerol atmosphere in an air-tight dessicator. The dessicator and samples were placed in the oven for two hours at 60° C. The glycolated samples were then analyzed.

After the glycolated samples were analyzed, the tiles were placed in a muffle furnace for one hour at 300° C. Samples were then allowed to cool in a desiccator before analysis. After the 300° C heat treatment and analysis, samples were returned to the muffle furnace for an hour and a half at 550°C. Samples were again cooled in a desiccator and analyzed for the final time.

Jade software (Materials Data Incorporated, 2005) was used for a semi-quantitative analysis of the untreated silt-clay XRD run. A variable parabolic filter with a threshold of three and cutoff of four percent was used to detect 2-theta mineral peaks. To identify select minerals, results from Jade were compared to known 2-theta peaks from Chao (1969) and Downs and Hall-Wallace (2003). For clay mineral identification, manual inspection of peak signatures was used to observe peak shifts associated with each pretreatment. Observed peaks were classified as normal or weak, with weak peaks defined as being barely distinguishable from the X-ray background.

Heavy Mineral Identification

Eight samples from both Louis and Fiddlers cores were prepared for heavy mineral identification (Tables 1 and 2). Sediment remaining after particle-size and X-ray diffraction procedures was used.

To isolate the medium- to coarse-silt fraction (20- 50μm) samples were wet-sieved to remove any sands. Fine-silts and clays were removed using a 20μm filter cloth. The heavy mineral fraction was separated from the light mineral fraction of each sample using a polytungstate solution with a specific gravity of 2.86 following procedures modified from Dahms (1991, 1993). Heavy mineral separates for each sample were washed in acetone and applied to a glass slide using an optical adhesive and cured overnight.

Table 1
Fiddlers Lake heavy mineral samples

Sample	Depth (cm)
Fid_1B_44	122
Fid_3L_14	192
Fid_3L_74	252
Fid_4L_57	332
Fid_5L_72	443
Fid_7L_32	599
Fid_8L_87	730
Fid_9L_97	838

Table 2
Louis Lake heavy mineral samples

Sample	Depth (cm)
Lou_4L_82	302
Lou_5L_31	352
Lou_5L_81	402
Lou_5L_91	412
Lou_6L_09	422
Lou_7L_13	522
Lou_8L_79	672
Lou_10L_46	813

Heavy minerals were identified and counted on eight of the sixteen prepared slides using a line point-counting technique (Carver, 1971). Since total grains were not counted, results from line point-counting method are presented as frequencies. For identification, a Meiji ML9000 polarizing microscope with 10X eyepieces was used. The 0.25 objective was used for line point-counting while the 0.65 objective was utilized for identification. Mineral identification was aided by references from Heinrich (1965), Kerr (1959), Milner (1962), and Scholle (1981).

The threshold for confident representation of heavy minerals present (Carver, 1971) was set at 200 grains. Results were number frequencies of six mineral-identification categories: plutonic zircon, volcanic zircon, oxyhornblende, green-brown hornblende, non-opaque other, and opaque. Due to the wide discrepancy of grain quantity between slides, only two slides met the nominal 200-grain minimum. Slides with less than two hundred grains were tallied with total grains encountered.

Loss-On-Ignition

Samples were air-dried prior to the loss-on-ignition procedure. Average sample weight was 1.5-2 grams. Sediment was gently disaggregated using a mortar and pestle. Crucible tare weights were measured and then air-dry sample weights were recorded. Samples were heated at 110° C for fifteen hours to remove additional moisture and reweighed once samples had cooled. To oxidize organic matter, samples were placed in a muffle furnace for two hours at 450° C and then weighed after cooling. Between weighing and heat treatments, samples were placed in a desiccator to prevent moisture retention. Weight data were entered into a spreadsheet and moisture factor, percent moisture, and percent organic matter were calculated.

CHAPTER 4

RESULTS

Core Descriptions

Descriptions of the sediment cores were performed by Dennis Dahms and staff at the LRC. Initial core descriptions (ICD) included written and photographic documentation, visual descriptions of sedimentary structures, mineralogy, and biologic components (Myrbo, 2005). The lithostratigraphic units, structure and descriptions referred to in this section come from the core ICDs (Figure 3 and Appendix D). Lithostratigraphic units were numbered from the top-down. These units were not necessarily correlative between cores but represented distinct sedimentological characteristics within each core.

Fiddlers Lake Core

The Fiddlers Lake core consisted of 7.59 meters of sediment extracted in nine piston drives. The top of the core was approximately ninety centimeters below the sediment-water interface. The ninety centimeter difference between the sediment-water interface and the top of the core was included in the depth measurements of the samples.

The sediment of Fiddlers Lake was divided into five lithostratigraphic units (Table 3). Unit #1 consisted of 159 centimeters of fibrous, peaty, organic sediment. Visual description classified the unit as peat or organic-rich silt. Plant macro-fragments were abundant and the structure was massive to crudely banded. The organic fraction

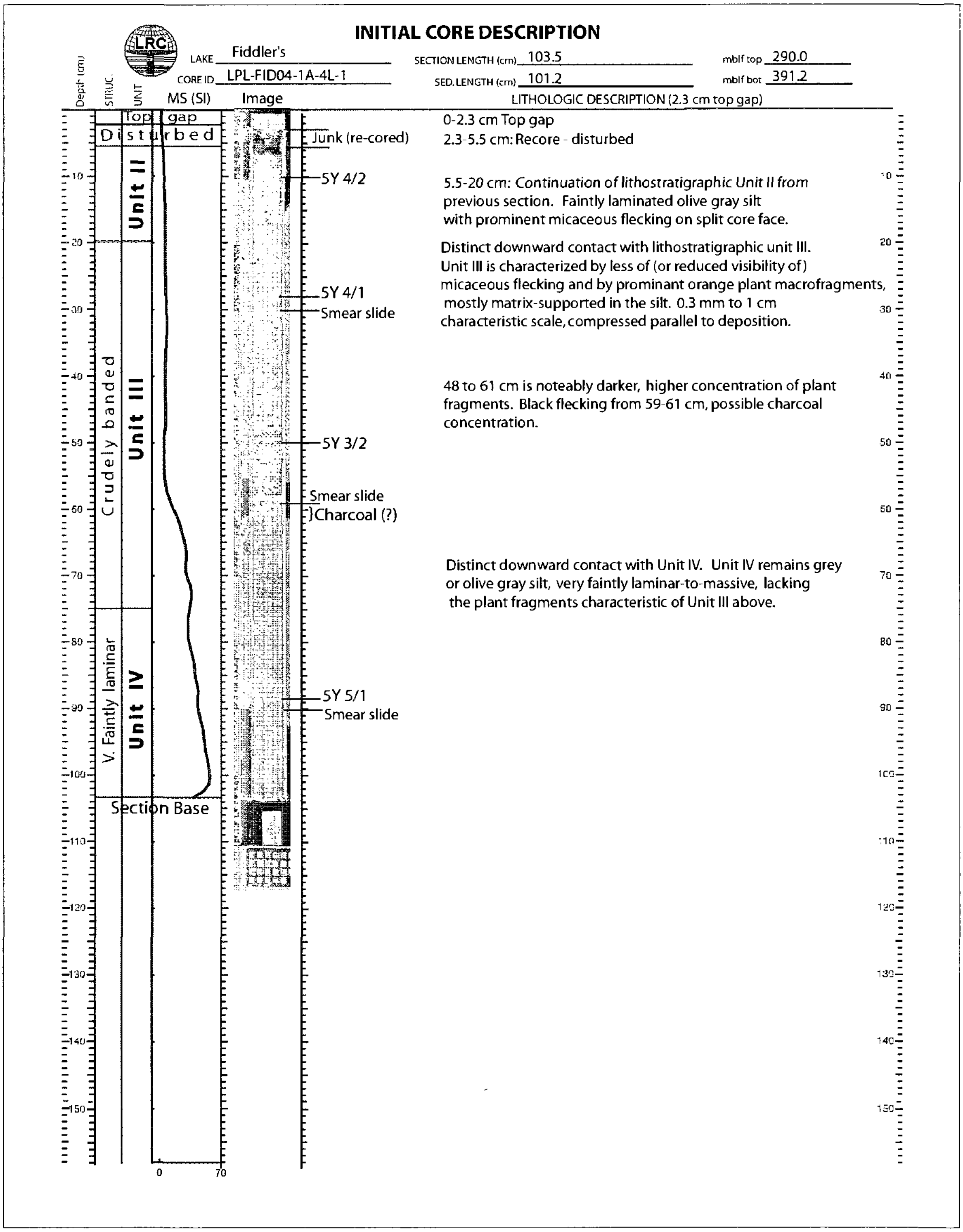


Figure 3: Example of initial core description (ICD) sheet for Fiddlers Lake core, drive 4L.

Table 3
Fiddlers Lake lithostratigraphic units

Unit	Thickness (cm)	Description
1	159	Fibrous organic peat or peaty-silt
2	46	Faintly-laminated silt
3	55	Crudely-banded silt with plant macrofragments
4	487	Massive to very-faintly laminated silt
5	12	Fine sands and gravels

became darker and coarser in the basal thirty centimeters before a distinct downward contact with Unit #2.

Unit #2 was composed of forty-six centimeters of faintly-laminated silt with scattered pebbles and micaceous flecking. Unit #3 was also predominantly silt yet with less micaceous flecking and more plant macro-fragments than Unit #2. The unit was fifty-five centimeters thick and crudely banded.

Unit #4 was composed of 487 centimeters of massive to very-faintly laminated silt. This unit lacked the plant macro-fragments found in Unit #3 above while micaceous flecking was again prominent. Flecks and stringers of vivianite were present in the upper hundred centimeters of this unit. Vivianite is a secondary mineral formed after deposition and the prevalence of vivianite may indicate cold, dry conditions (Sapota, Aldahan, & Al-Aasm, 2005). Graded intervals of coarse silts or fine sands occurred irregularly. Laminations were distinct enough for Dennis Dahms to measure varve thickness on the basal 270 centimeters of Unit #4 and estimate accumulation rate (personal communication, April 15, 2010).

Unit #5 was twelve centimeters thick and was composed of fine sands and gravels at the bottom of the core. This coarse sediment apparently represents an erosion surface or coarse outwash from the lateral moraine that dammed Fiddlers Lake.

Louis Lake Core

The Louis Lake core consisted of approximately 9.4 meters of sediment extracted from eleven piston drives. There were four lithostratigraphic units described in the core's ICD (Table 4). Laminations in the Louis Lake core were clearer than Fiddlers Lake and Dennis Dahms measured varve thickness for approximately 600 centimeters of sediment which included Units 2, 3 and 4.

Table 4
Louis Lake lithostratigraphic units

Unit	Thickness (cm)	Description
1	300	Massive to faintly-laminated organic-rich silt
2	46	Same as Unit #1 but faintly mottled
3	87	Faintly-laminated silt
4	506	Finely laminated silty clay

Lithostratigraphic Unit #1 was composed of massive to faintly-laminated organic-rich silt. This unit was marked by abundant micaceous flecking, scattered grains of sand and an interval of semi-hardened bands of limonite (or hydrated iron oxide). Sand content decreased toward the bottom of this unit and micaceous flecking became less prominent. Unit #1 was three hundred centimeters thick and the contact with Unit #2 was gradational.

Unit #2 was approximately forty-six centimeters thick and was generally similar to Unit #1 except for less micaceous flecking and a faintly-mottled appearance. Coarse bands identified as charcoal were present at the top of the unit and diminished toward the bottom.

The boundary between Unit #2 and #3 was gradational and arbitrarily marked. Unit #3 was a massive to faintly-laminated silt with higher proportions of clay. The unit was approximately eighty-seven centimeters thick and contained occasional sand grains and thin stringers of vivianite.

A downward gradational contact to Unit #4 was marked by more distinct laminations. Unit #4 was approximately 506 centimeters thick and was composed of silty clay that was finely laminated. Irregular intervals of sand bands occurred throughout the unit. One band of vivianite occurred near the top of this unit. The bottom of this unit and the core did not represent the base of Louis Lake sediment.

Particle Size Analysis

Fiddlers Lake PSA

Results from the particle-size analysis (PSA) generally matched the visual description of silt-rich sediment from the ICDs (Figure 4). Of the fifty-five samples analyzed for this study, twenty-one were classified as silt. Twelve samples were classified as clayey silt and twenty-two samples were sandy silt. Silt was the dominant grain size overall and averaged 74%, while sand and clay averaged 15% and 12%, respectively.

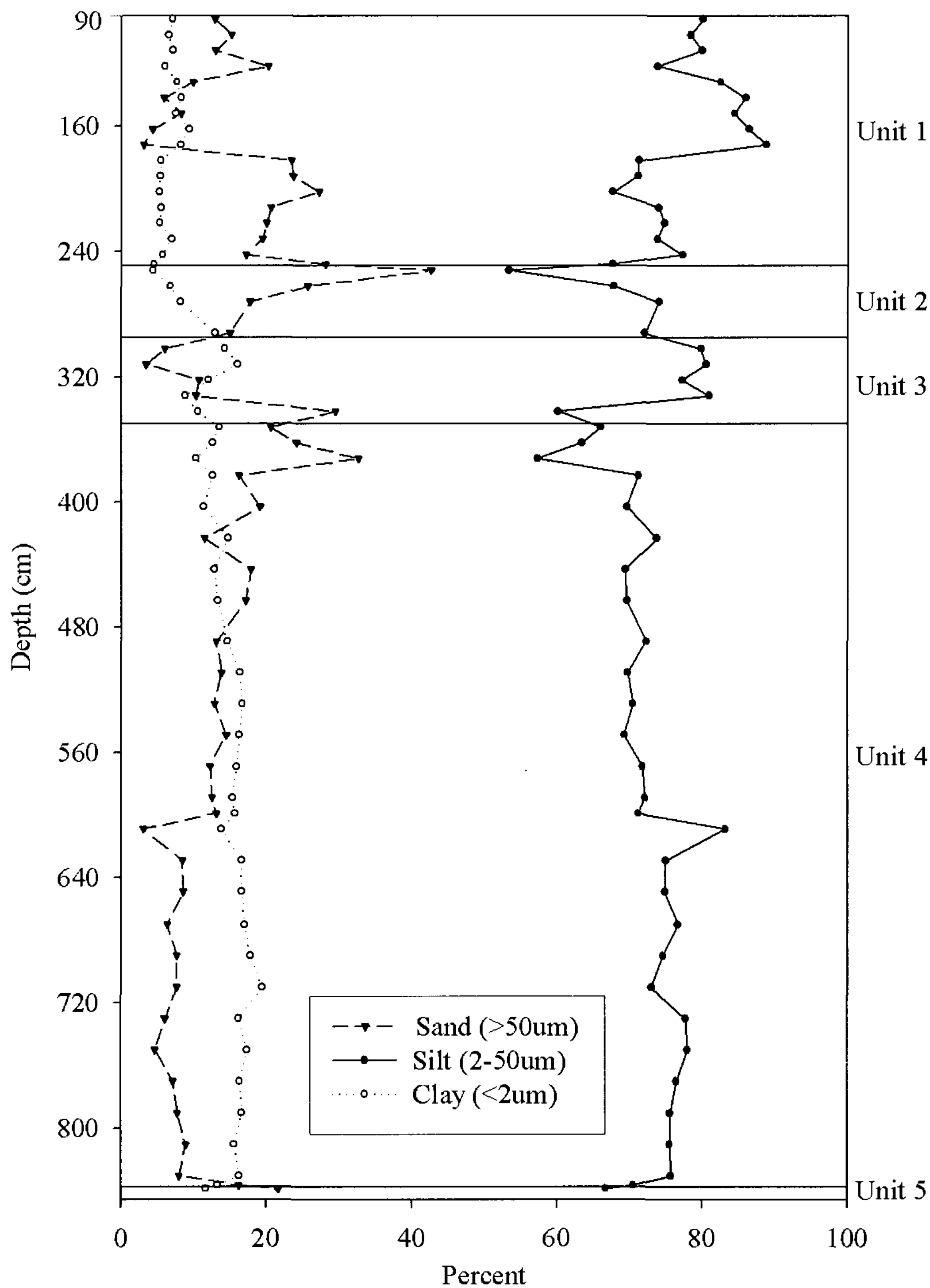


Figure 4: Particle size results for Fiddlers Lake core.

Of the seventeen PSA samples from Unit #1, nine were classified as silt and eight were sandy silt. Silt content was high and ranged from 67 to 87%. Sand content ranged from 3 to 27% and inversely reflected variations in silt percentages. Clay content was low and steadily measured between 4 and 9%.

Of the four samples from Unit #2, all were classified as sandy silt. Following Unit #1, sand values in Unit #2 increased dramatically to 43% before steadily decreasing to 15%. Silt values increased from 53% to 72%, while clay slightly increased from 4% to nearly 13%.

Unit #3 contained four silt and one sandy silt classifications. Silt values were stable near 80% before dropping to 60% on the last sample of the unit. Sand values increased from 3% to 29% while clay varied between 8% and 16%.

The twenty-eight samples from Unit #4 showed variability in their grain-size distribution though sand and silt were inversely correlated. Generally, values of silt and clay increased throughout the unit while sand decreased. Silt percentage ranged from 57% to 83%. Clay values varied between 10% and 19%. Sand varied widely from 3% to 33%.

The single sample from Unit #5 was classified as sandy silt. Sand, silt, and clay percentages for the sample were 22%, 67%, and 18%, respectively. An abrupt coarsening was observed in the last sample from Unit #4 and the single Unit #5 sample as the base of the core apparently reached an erosional surface or outwash deposit.

Louis Lake PSA

Samples from the Louis Lake core were generally coarser than samples from Fiddlers Lake (Figure 5). Silt was still the dominant grain size and averaged 69%, while sand and clay averaged 21% and 10%, respectively. Sand values were at their highest in Units #1 and #2 while there was more silt and clay in Units #3 and #4. Of the sixty-seven samples analyzed from the Louis Lake core, thirty-one were classified as silt and thirty-three were sandy silt. One sample was classified as clayey silt and two samples were classified as silty sand.

There were no discernible trends throughout Unit #1. Clay content was relatively stable and did not exceed 12%. Silt and sand values were irregular and inversely related. Silt percent ranged from 43% to 82%. Sand percents were between 7% and 51%. Sample Lou_4L_12 at a depth of 232 centimeters recorded both the highest sand percent (51%) and lowest silt percent (43%) of the core. Of the thirty samples in Unit #1, twenty-two were classified as sandy silt. Six samples were classified as silt and two were silty sand.

All five samples from Unit #2 were sandy silt. Clay content rose slightly from 6% to just over 9%. Sand content decreased downward through the unit from over 40% to 22%. Between samples Lou_4L_102 and Lou_5L_11 (depths of 322 and 332 centimeters, respectively), silt content increased from 52% to 71% and remained high to the bottom of the Louis Lake core.

In the eight samples from Unit #3, six were sandy silt along with one silt and one clayey silt. Sand content ranged between 10% and 25% and generally decreased downward through the unit. Clay values were steady and averaged 14%. Silt values

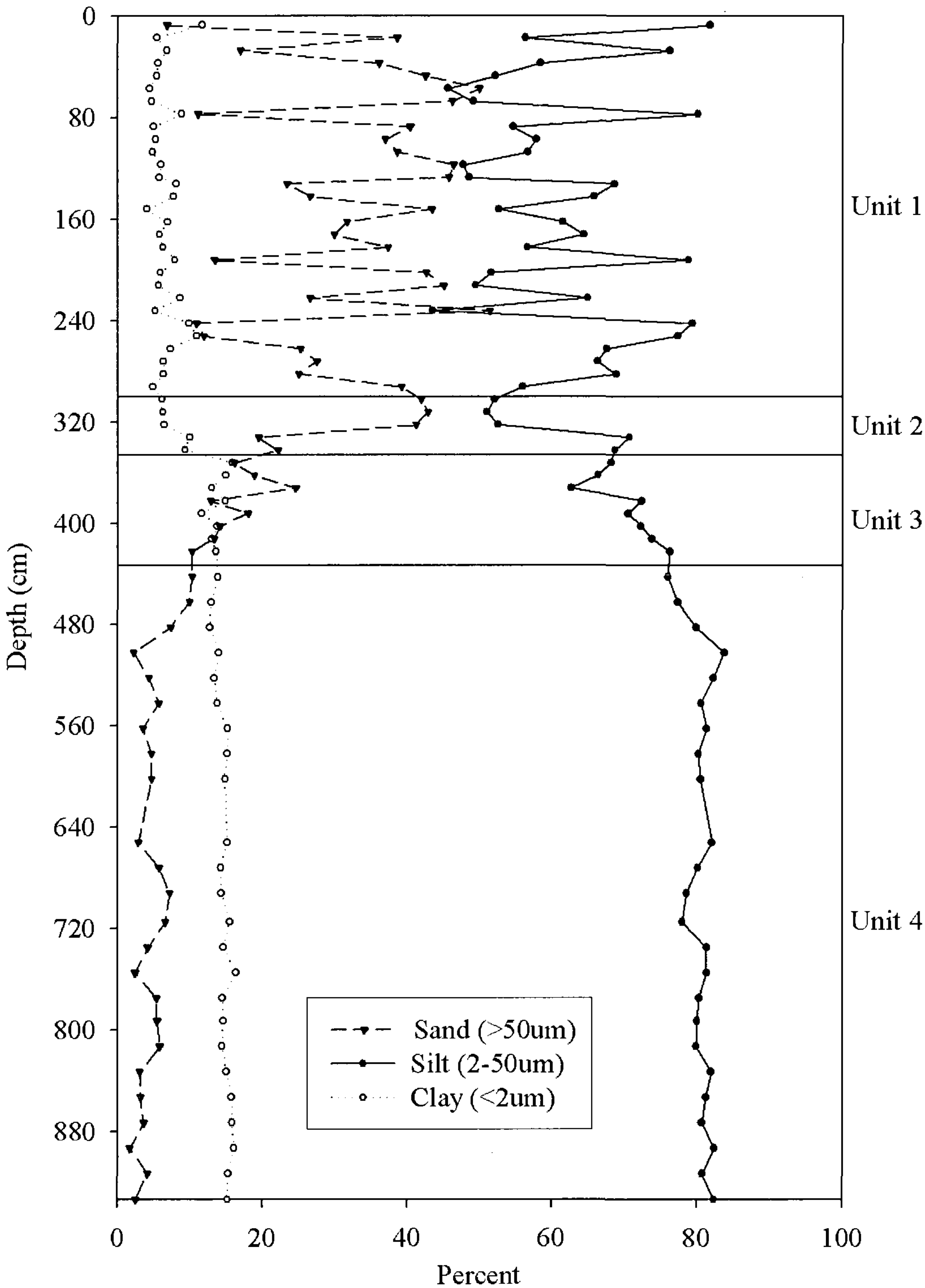


Figure 5: Particle size results for Louis Lake core.

averaged 70%. The samples from units #2 and #3 apparently represented a transition between the variable Unit #1 and stable Unit #4 (Figure 5).

Sediment in Unit #4 was characterized by the least variation in PSA and dominated by silt. Silt content averaged 81% and did not fall below 76%. Clay content ranged between 13% and 16%. Sand content was lowest in Unit #4 and did not exceed 10%. All twenty-four samples from Unit #4 were classified as silt.

X-Ray Diffraction

Fiddlers Lake XRD

Forty-four samples from the Fiddlers Lake core were analyzed for silt and clay mineralogy. The number of silt minerals identified in each sample was variable but generally increased with depth (Figure 6). Present in over 80% of the samples, muscovite, quartz and tourmaline were the most frequently identified silt minerals (Table 5). Biotite was not identified in Unit #1 (Appendix B).

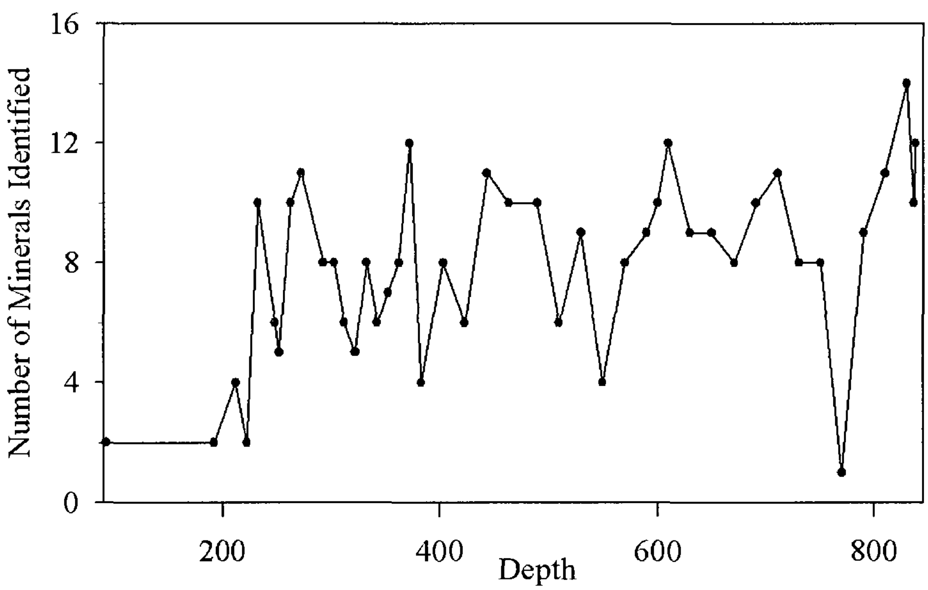


Figure 6: Fiddlers Lake silt identification totals

Table 5
Fiddlers Lake frequency of silt mineral identification

Mineral	Count	Percent
Muscovite	43	97.73
Quartz	38	86.36
Tourmaline	37	84.09
Microcline	33	75.00
Clinopyroxene	31	70.45
Zircon	29	65.91
Titanite	21	47.73
Biotite	17	38.64
Magnetite	17	38.64
Plagioclase	15	34.09
Augite	13	29.55
Orthoclase	13	29.55
Garnet	6	13.64
Zeolite	6	13.64
Hypersthene	4	9.09
Rutile	3	6.82
Kyanite	1	2.27
Apatite	0	0.00
Epidote	0	0.00
Hornblende	0	0.00
Olivine	0	0.00
Orthopyroxene	0	0.00
Zoisite	0	0.00

Of the forty-four samples in the Fiddlers Lake core, kaolinite and vermiculite were the most common clay minerals (Table 6). Kaolinite and chlorite were likely present due to local geology and weathering of the bedrock. Vermiculite and smectite were thought to be non-native and transported by eolian forces (D. Dahms, personal communication, March 22, 2010). Smectite was only identified in Unit #4 (Figure 7 and Appendix B). The only clay peak observed in Unit #1 was classified as weak.

Table 6

Fiddlers Lake clay mineral counts

Mineral	Normal peak	Weak peak	Total
Kaolinite	28	9	37
Vermiculite	16	7	23
Chlorite	5	11	16
Smectite	11	0	11
Illite	0	0	0

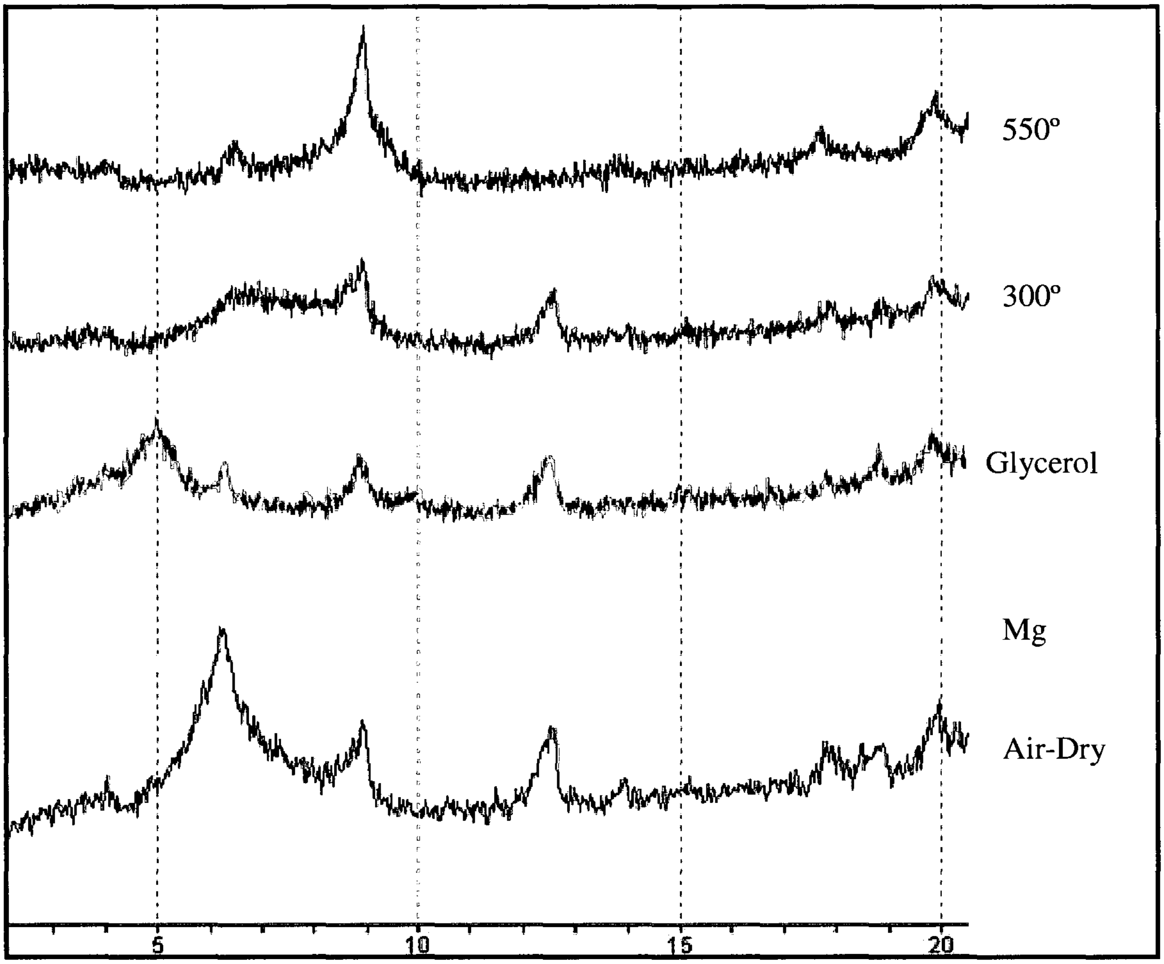


Figure 7: XRD peak signatures of clay pretreatments for Fid_9L_49. The peak shift from 6.2° to 5° 2-theta of the glycerol sample identifies smectite.

Louis Lake XRD

X-ray diffraction was performed on sixty-six samples from the Louis Lake core. The number of silt minerals identified in each sample ranged between one and thirteen (Figure 8). Similar to Fiddlers Lake, muscovite, tourmaline, and quartz were identified most frequently (Table 7). Zircon was also prominent, being identified in 89% of samples. Biotite and plagioclase were identified in 40% and 48% of samples, respectively. Kaolinite was the most frequently identified clay mineral (Table 8).

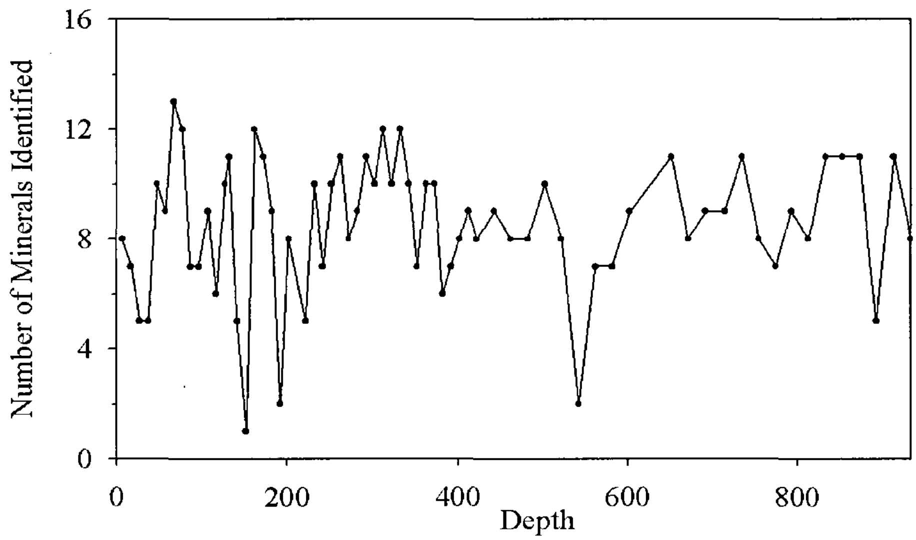


Figure 8: Louis Lake silt identification totals

Table 7
Louis Lake frequency of silt mineral identification

Mineral	Count	Percent
Muscovite	63	95.45
Tourmaline	62	93.94
Zircon	59	89.39
Quartz	57	86.36
Microcline	52	78.79
Clinopyroxene	40	60.61
Orthoclase	32	48.48
Plagioclase	32	48.48
Titanite	31	46.97
Magnetite	29	43.94
Augite	27	40.91
Biotite	27	40.91
Kyanite	9	13.64
Hypersthene	8	12.12
Rutile	6	9.09
Garnet	4	6.06
Hornblende	2	3.03
Olivine	2	3.03
Apatite	1	1.52
Orthopyroxene	1	1.52
Epidote	0	0.00
Zeolite	0	0.00
Zoisite	0	0.00

Table 8
Louis Lake clay mineral counts

Mineral	Normal Peak	Weak Peak	Total
Kaolinite	34	16	50
Vermiculite	22	13	35
Chlorite	0	24	24
Smectite	11	5	16
Illite	0	0	0

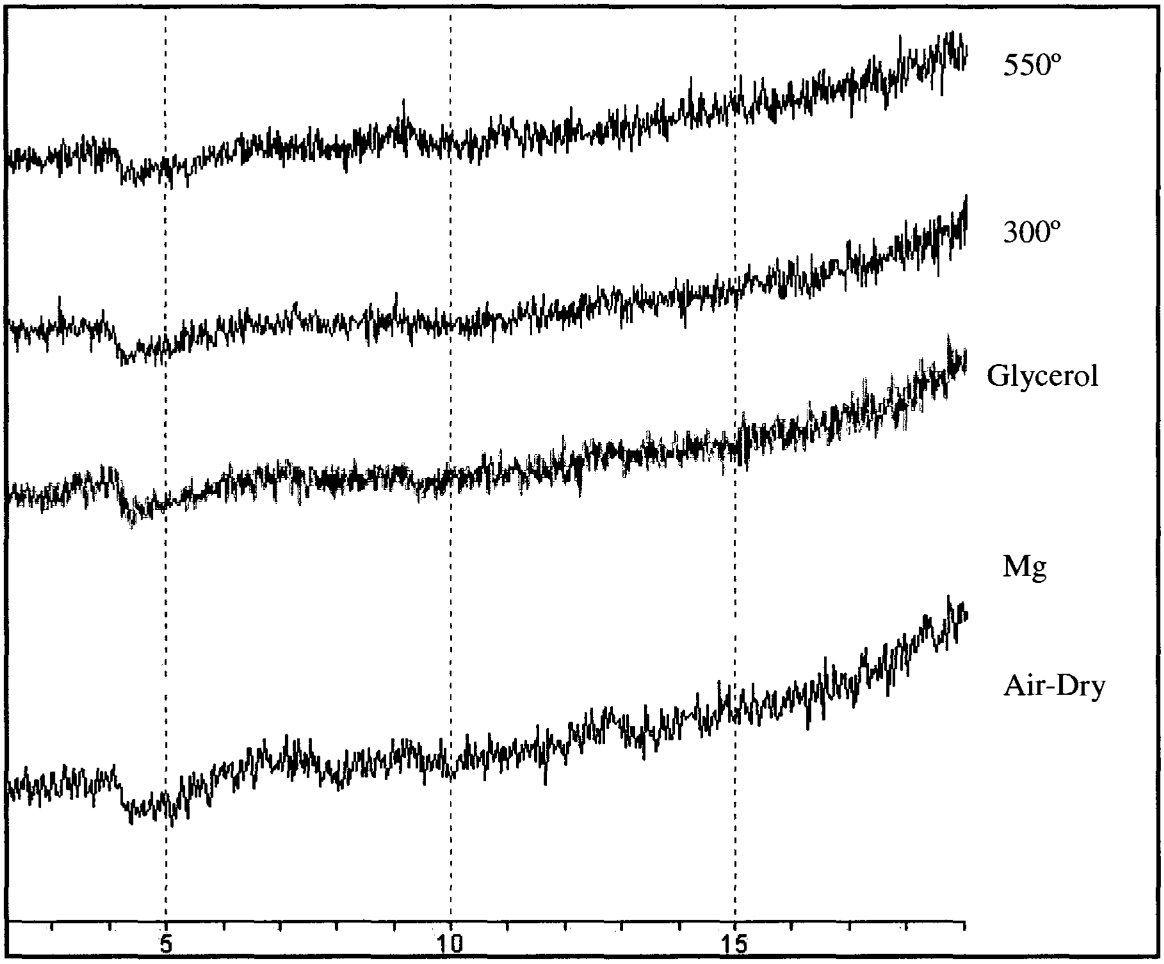


Figure 9: Weak XRD peak signatures of clay pretreatments for Fid_3L_34

Loss-On-Ignition

Fiddlers Lake LOI

Organic matter contents obtained from LOI analysis for the Fiddlers Lake core averaged 14%. Overall, values decreased down-core and ranged from 49% to 1% (Figure 10). The highest value was recorded in Fid_3L_64 at a depth of 242 centimeters. The lowest value was sample Fid_10L_07 at 845 centimeters. From the top of the core to a depth of 332 centimeters, values were high and averaged 27%. Below 334 centimeters, organic matter values did not exceed 5%

Of the seventeen samples in Unit #1, the average organic matter was 35%. Units 2 and 3 each had five samples and averaged 13% and 8%, respectively. Unit #4 averaged 3% from twenty-eight samples. Unit #5's average was 2% for four samples.

Louis Lake LOI

Average organic matter content for Louis Lake samples was 10%. Similar to Fiddlers Lake core, values decreased down-core. Values were less variable, however, and ranged from 25% to 3% (Figure 11). Sample Lou_4L_42 at a depth of 262 centimeters recorded the highest percent while Lou_10L_46 at 813 centimeters recorded the lowest.

Average organic matter percent for twenty-one samples from Unit #1 was 18%. Unit #2 averaged 13% from five samples and Unit #3 averaged 5% from eight samples. The average for the twenty-four samples from Unit #4 was 4%. Values were relatively high in the upper 362 centimeters and averaged 17%. Below 362 centimeters, values averaged 4% and did not exceed 6%.

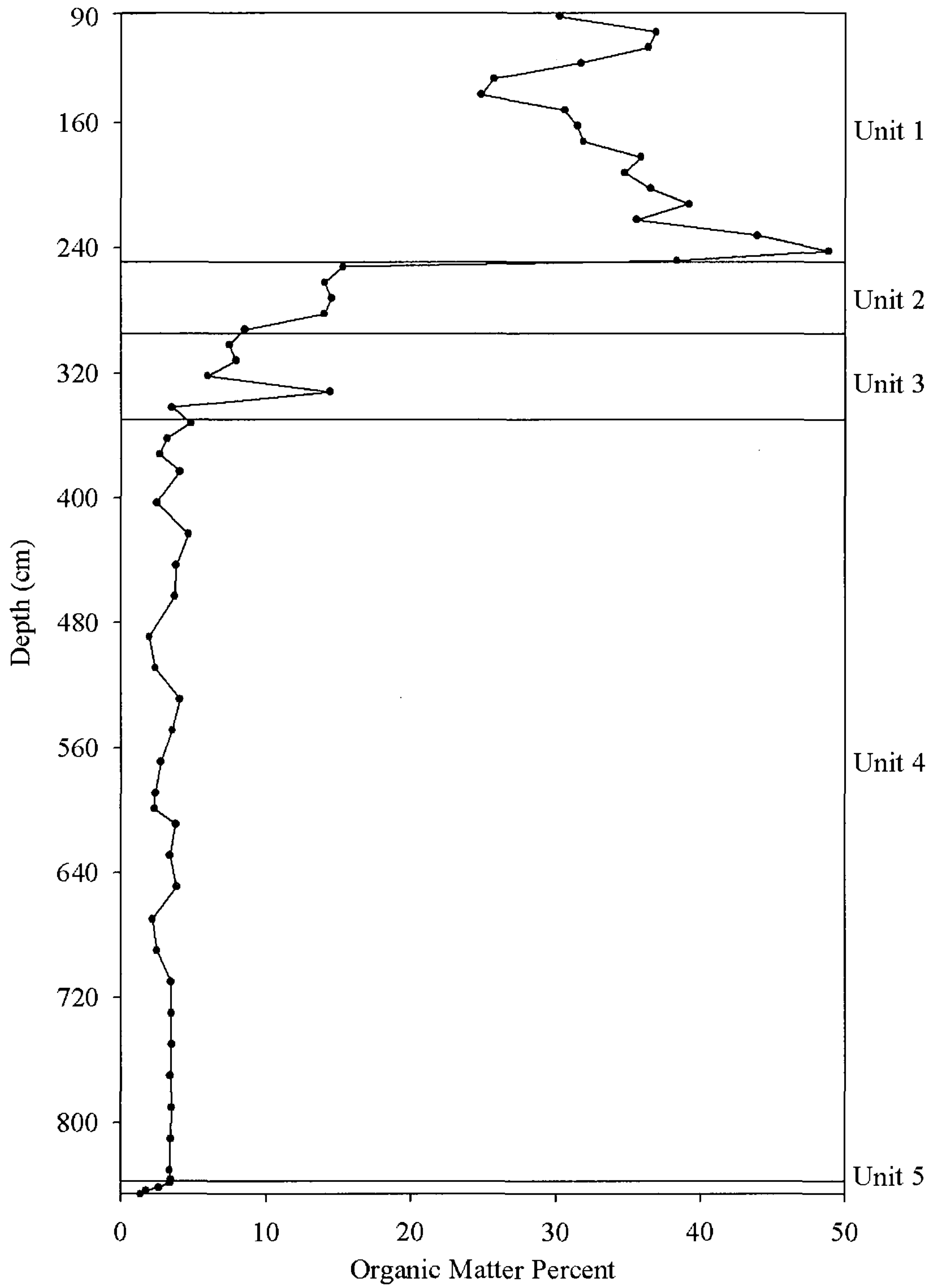


Figure 10: Fiddlers Lake LOI values

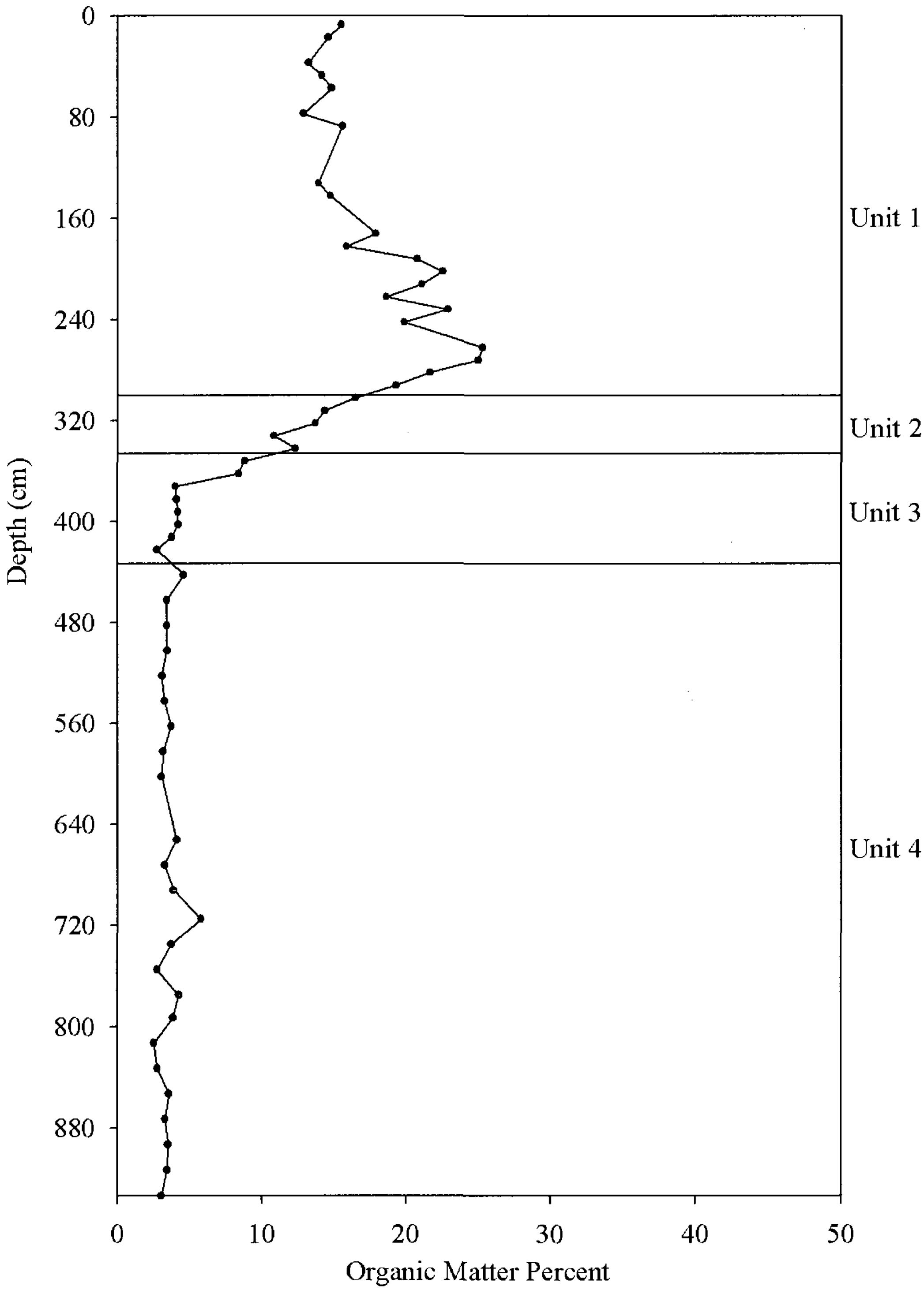


Figure 11: Louis Lake LOI values

Heavy Mineral Analysis

Fiddlers Lake HMA

Eight samples from the Fiddlers Lake core were analyzed for heavy mineral content. Four of the eight were selected for counting (Fid_1B_44, Fid_4L_57, Fid_7L_32, and Fid_9L_97). Results from three samples did not meet the 200-grain minimum for confident representation and were presented as total number of grains encountered (Table 9). Only Fid_9L_97 from Unit #5 met the nominal 200-grain minimum allowing for confident representation and had a heavy mineral count of 556. Frequency results from Fid_9L_97 are presented in Table 10. The prevalence of green-brown hornblende and volcanic zircon grains was thought to be indicative of eolian contribution (Dahms, 1993).

Table 9
Fiddlers Lake heavy mineral counts

Sample	Lith. Unit	Depth (cm)	Count
Fid_1B_44	1	122	1
Fid_4L_57	3	332	4
Fid_7L_32	4	599	64
Fid_9L_97	5	838	556

Table 10
Heavy mineral analysis results for Fid_9L_97

Mineral Category	Frequency
Plutonic Zircon	8
Volcanic Zircon	1
Oxyhornblende	22
Green-brown hornblende	24
Non-opaque other	411
Opaque	90
Total	556

Louis Lake HMA

Eight samples from the Louis Lake core were analyzed for heavy mineral content. Four of the eight were selected for counting (Lou_4L_82, Lou_5L_81, Lou_7L_13, and Lou_10L_46). Results from three samples did not meet the 200-grain minimum for confident representation and were presented as total number of grains encountered (Table 11). Frequency results from Lou_7L_13 are presented in Table 12.

Table 11
Louis Lake heavy mineral counts

Sample	Lith. Unit	Depth (cm)	Count
Lou_4L_82	2	302	7
Lou_5L_81	3	402	64
Lou_7L_13	4	522	254
Lou_10L_46	4	813	110

Table 12
Heavy mineral analysis results for Lou_7L_13

Mineral Category	Frequency
Plutonic Zircon	2
Volcanic Zircon	0
Oxyhornblende	7
Green-brown hornblende	5
Non-opaque other	200
Opaque	40
Total	254

Sediment Age Data

Supplemental age data for the cores were provided by Geiss (personal communication, February 15, 2010). Radiocarbon dating was performed on six samples from the additional Fiddlers Lake core at the Keck-CCAMS facility at the University of California at Irvine (Table 13). Radiocarbon dates were calibrated using CALIB 6.0.1

(Stuvier & Reimer, 2010). For sediment older than the earliest radiocarbon sample, ages were estimated using varve counts to measure sediment accumulation rates. The two Fiddlers Lake cores were correlated using rock magnetic data including magnetic susceptibility and remanence parameters (C. Geiss, personal communication, March 8, 2010). A composite age model for Fiddlers Lake was calculated by Geiss (2010) using a polynomial fit through the calibrated ages.

Post-glacial sediment at Fiddlers Lake was too weakly magnetized to allow correlation with Louis Lake (Geiss et al., 2007, 2009); therefore, the post-glacial record of changes at Louis Lake could not be numerically constrained. Age data from the Fiddlers Lake core were used to establish a chronology of environmental changes in the Little Popo Agie Basin.

Table 13
Radiocarbon and calibrated ages for Fiddlers Lake core samples

Drive Section	Depth	UCIAMS Lab #	14-C Age	14-C Error +/-	Calibrated Age BP
1L	62	41905	5015	20	5667-5859
2L	20-25	41906	7065	20	7867-7938
2L	70-75	41907	8530	20	9502-9537
3L	0-5	41908	9135	25	10237-10280
3L	30-40	41909	9390	25	10578-10658
4L	12-20	42032	13005	30	15235-15868

CHAPTER 5

DISCUSSION AND CONCLUSIONS

A Paleolimnoligical Record of Environmental Changes

During the Pleistocene, lateral moraines of the valley glaciers in the Little Popo Agie Valley dammed the basins of Fiddlers and Louis lakes. Consequently, these blocked basins began filling in while recording sedimentological characteristics of the changing environment within each isolated basin.

To establish a record of sedimentological variability for Fiddlers and Louis lakes, multiple paleolimnological proxies were examined. The results from the both lakes' cores showed similar responses to local and regional glacial/post-glacial environmental changes. Although the record from Louis Lake is not numerically constrained, the responses detected from the present analyses resembled trends in Fiddlers Lake making it possible to assume the changes in both lakes were corroborative and generally synchronous.

Based on the results, four phases of sedimentological characteristics were identified in each core: full-glacial, late-glacial, transitional and post-glacial. The phases listed in this chapter do not necessarily correspond to the lithostratigraphic units derived from the ICDs, which were based on visual sediment characteristics (Figure 12). The phases listed hereafter relate to consistent, multi-proxy responses in both lakes. Subsequent graphs have also been modified to illustrate these phases and have abandoned the lithologic unit classification.

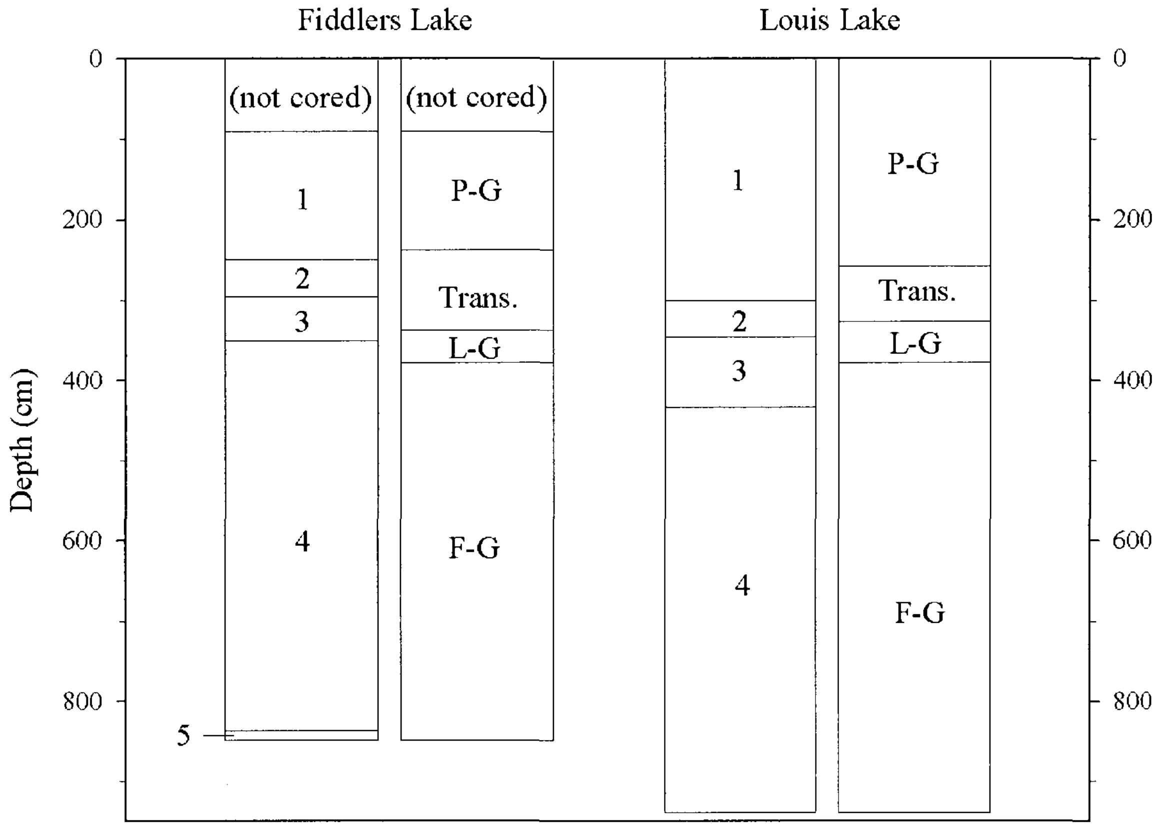


Figure 12: Comparison between lithostratigraphic units and phases.

Full-Glacial

The sedimentological characteristics of the full-glacial period reflect the cold, stable conditions experienced in the Little Popo Agie Basin prior to 17,400 cal. years BP. The first phase of sedimentation was marked by infilling of the newly-dammed basins. In the Fiddlers Lake core, the bottom-most sediment is composed of fine gravels and sands. These coarse sediments apparently represent an erosion surface or outwash from the newly emplaced lateral moraine that dammed the basin. Cores retrieved from Louis Lake did not reach this coarse layer.

The full-glacial unit of Fiddlers Lake was approximately 460 centimeters thick (Figure 13). For Louis Lake, the unit was approximately 560 centimeters thick though it is assumed to be thicker since the core did not reach the bottom (Figure 14). Louis Lake's larger drainage basin probably supplied more sediment during this time of infilling causing higher sedimentation rates and a thicker full-glacial package. According to Fiddlers Lake's composite age model, the full-glacial unit was deposited prior to about 17,400 cal. years BP. The estimated accumulation rate for this unit was approximately 2.26 millimeters per year, the highest of the core.

Full-glacial conditions were marked by silt-rich, inorganic sediment. The full-glacial phase was homogenous, made up the bulk of both cores and yielded uniform results. Silt values for full-glacial sediment averaged 73% in Fiddlers Lake and 79% for Louis Lake. Clay values were typically higher than sand, though there were a few exceptions near the top of this unit. The constancy of low sand values suggested that hydrologic surface inputs to both lakes were generally lower-energy and unable to transport large amounts of coarse particles and/or redistribute them within the lake. This may be due to lower precipitation or fewer large-storm events.

The average number of silt minerals identified was higher in Fiddlers Lake full-glacial sediment, and heavy mineral counts were higher for both Fiddlers and Louis lakes during this period. Orthoclase and plagioclase were less frequently identified in Louis Lake during the full-glacial than any other phase. Green-brown hornblende grains were found in nearly equal proportion to oxyhornblende grains in both Fiddlers and Louis

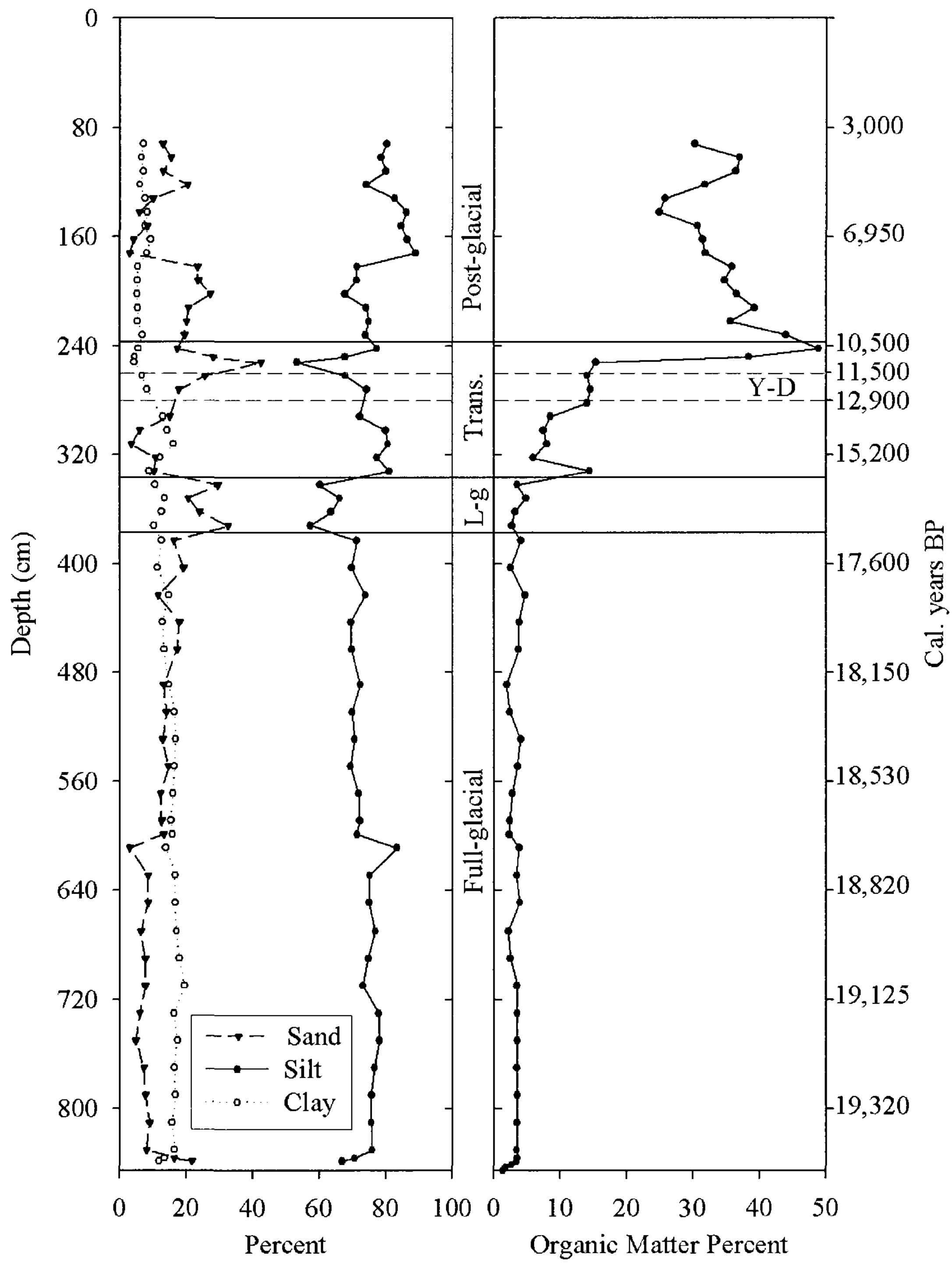


Figure 13: Fiddlers Lake comparison between PSA (left) and LOI (right).

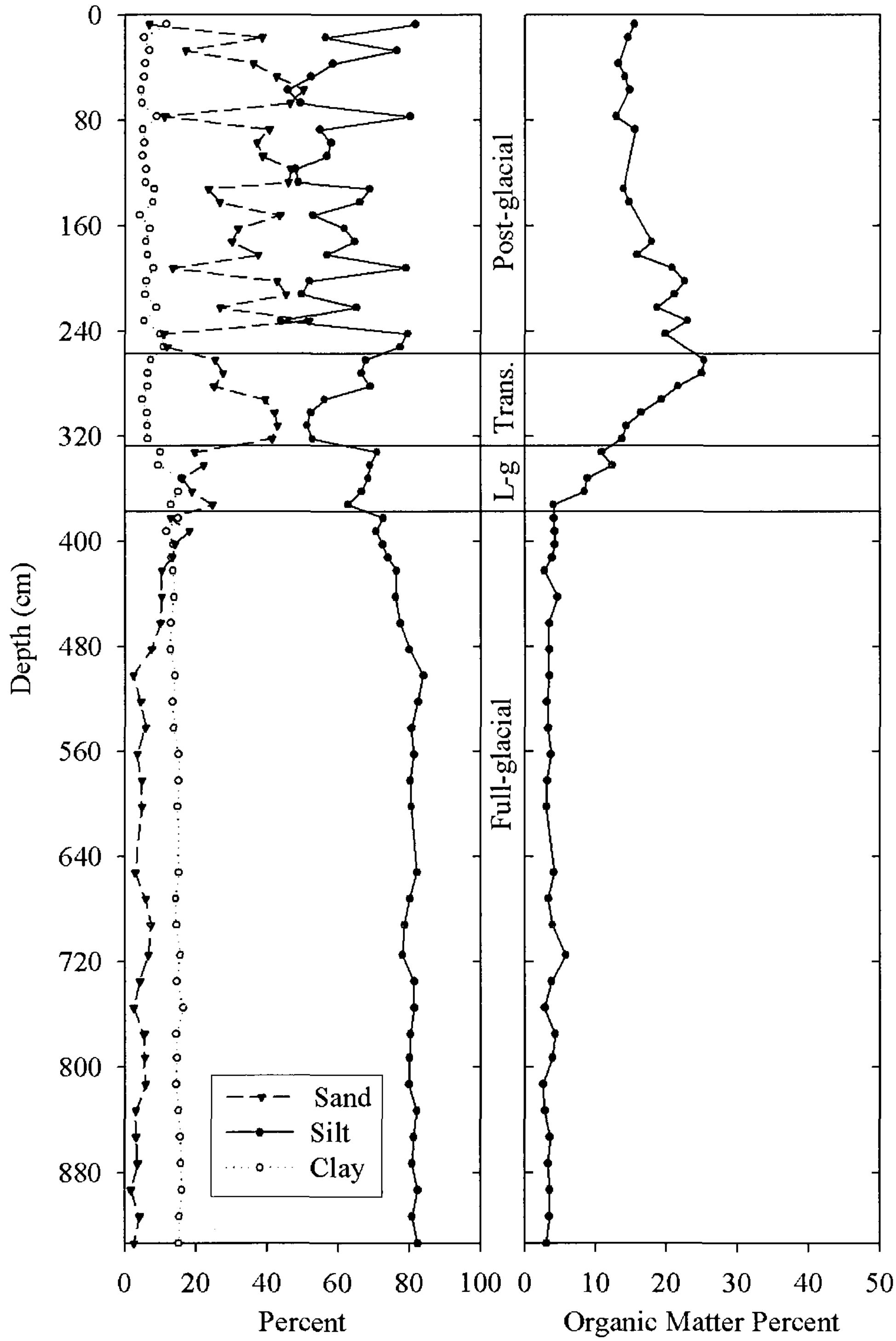


Figure 14: Louis Lake comparison between PSA (left) and LOI (right).

lakes' heavy mineral samples. With the exception of one late-glacial sample from Fiddlers Lake, the clay mineral smectite was only found in Fiddlers and Louis lakes' full-glacial sediment (Figure 15). Results from the XRD and heavy mineral analysis suggested eolian contribution was greater during the full-glacial. As eolian contribution was high, the full-glacial was evidently dustier when compared to the other phases.

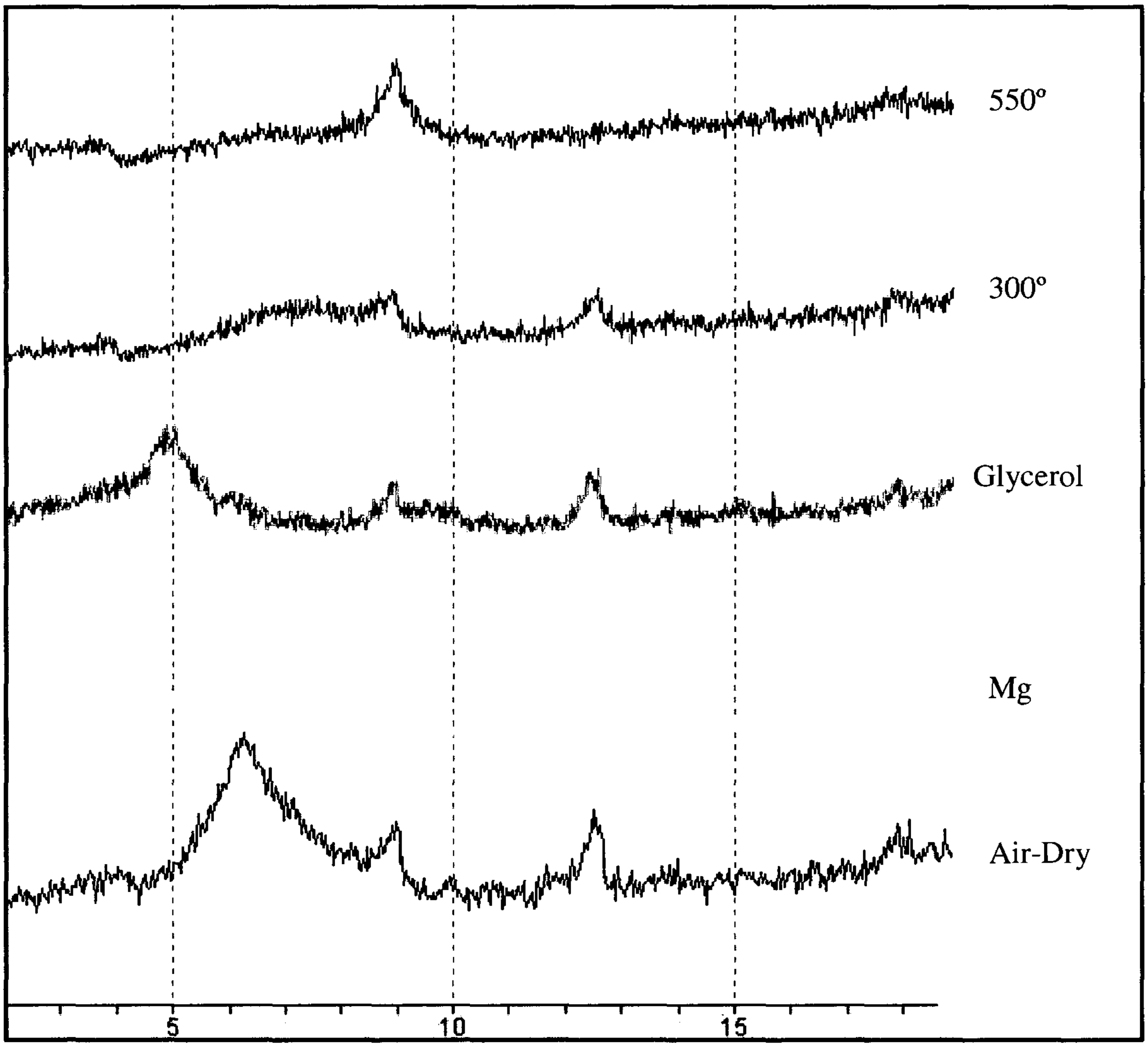


Figure 15: XRD peak signature of full-glacial sample (Lou_10L_86). Smectite, vermiculite, and kaolinite were commonly identified in full-glacial samples.

Organic matter content averaged 3% for Fiddlers Lake and 4% for Louis Lake. Full-glacial conditions would have hindered biologic productivity in the lake which may account for the paucity of organic matter. Dennis Dahms' estimate of ELA for the valley apparently places both lakes near upper tree line, thus vegetation had probably not been significantly established in either basin. Along with being situated near upper tree line, the colder and presumably drier full-glacial conditions probably resulted in much less vegetation in each basin and the amount of organic material being delivered to the lakes would have been minimal.

Late-Glacial

Above the full-glacial unit, particle-size results immediately responded to a changing environment and were the distinguishing characteristic of the late-glacial phase. The late-glacial phase was approximately forty centimeters thick (Fiddlers Lake) and fifty centimeters thick (Louis Lake). Using the age model from Christoph Geiss (2010), this phase roughly corresponds to the time period between 17,400 and 16,000 cal. years BP at Fiddlers Lake and accumulation rate was estimated to be 0.29 millimeters/year.

During the late-glacial, sand content increased and silt content decreased from the full-glacial values. Sand content in Fiddlers Lake averaged 26% in the late-glacial compared with 11% during the full-glacial. Louis Lake's late-glacial sand content averaged 20% compared with 6% during full-glacial. Both lakes showed a dramatic increase in coarser particles during late-glacial time (Figures 13 and 14) which may represent stronger stream flow, increased overland erosion and/or increased redistribution. Melting snowpack within each basin or increased regional precipitation may have been the cause of changing hydrologic energy and coarser grain sizes being deposited. The total amount of sediment being delivered to the lake was significantly less however when compared to the full-glacial as evidenced by accumulation rates.

Organic matter content began increasing in Louis Lake during this phase, though Fiddlers Lake's remained low. As the Little Popo Agie valley glacier receded in response to the changing environment during the late-glacial, vegetation gradually responded to the migration of tree line. As the basins became populated with plant life, organic matter contents in the sediment increased as biologic material was fed more directly into the lakes. Biologic productivity in the lakes likely increased with the warming environment as well. Fall et al. (1995) observed that peaks in aquatic algae pollen counts coincided with maximum LOI values.

The lack of organic matter deposition in Fiddlers Lake at this time was probably due to the difference in elevation between Fiddlers and Louis lakes. As Fiddlers Lake is approximately 800 feet higher, vegetation would be established later than Louis Lake as upslope migration delayed organic matter deposition.

There were no discernible trends in the silt mineralogy during the late-glacial. There were no smectite clay peaks in the Louis Lake samples (Figure 16). In Fiddlers Lake, the lowest late-glacial sample contained smectite, though no smectite was found in the rest of the core above this.

Based on magnetic susceptibility and remanence parameters, Geiss et al. (2007; 2009) described magnetic sediment older than approximately 16,000 cal. years BP as highly concentrated, coarse-grained detrital magnetite. According to the age model for

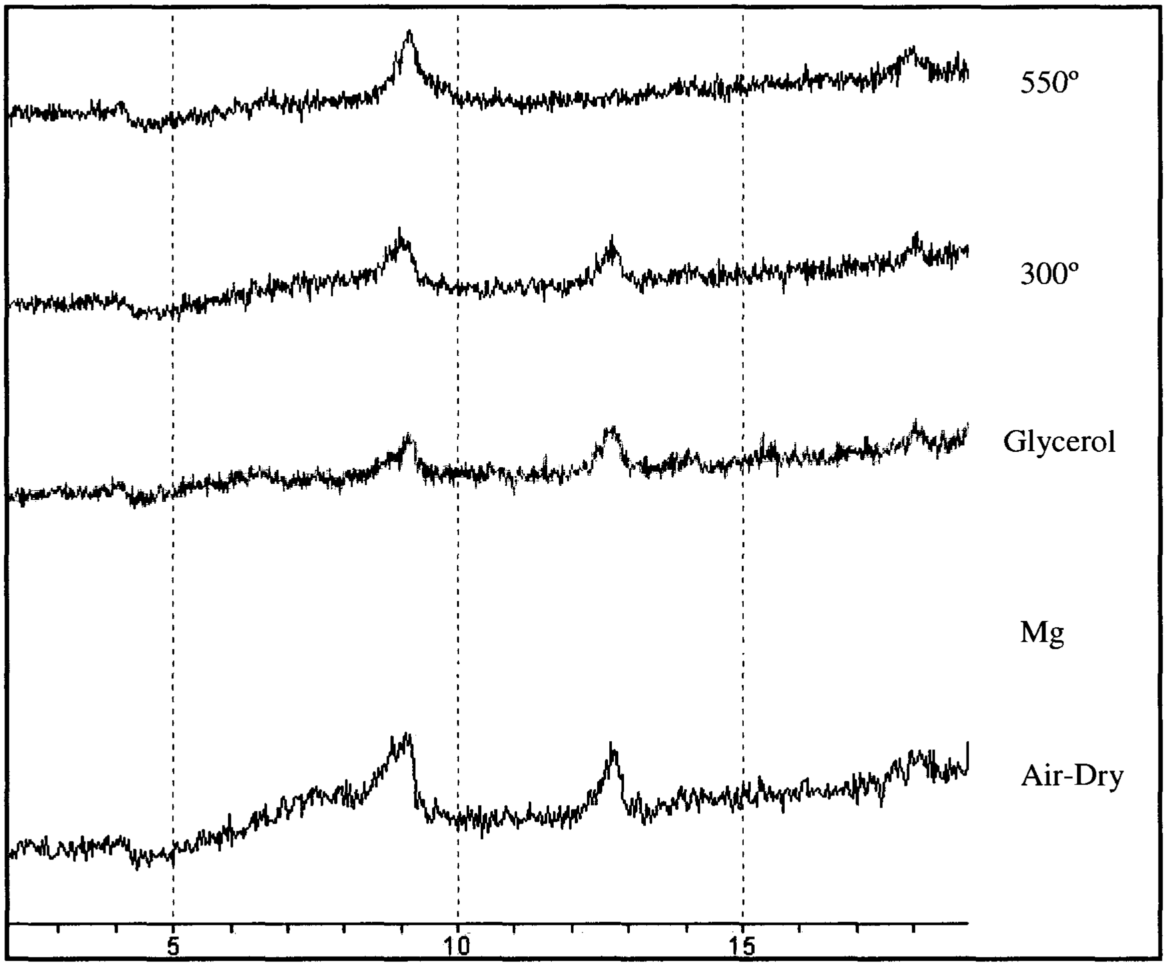


Figure 16: XRD peak signature of late-glacial sample (Lou_5L_41).

Fiddlers Lake (Geiss, 2010), this date occurred between the last late-glacial sample and the first transitional sample.

Transitional

The transitional unit was approximately one hundred centimeters thick (Fiddlers Lake) and seventy centimeters thick (Louis Lake). For the Fiddlers Lake core, this unit spans the period from approximately 16,000-10,700 cal. years BP (Geiss, 2010). Estimated accumulation rate for the transitional phase was 0.19 millimeters per year, the lowest accumulation rate of the core. The transitional phase was marked by increasing organic matter content and variable particle size distribution.

Organic matter contents during this period increased significantly, and by the end of the transitional phase, both Fiddlers and Louis lake cores reached their highest values. In Louis Lake, organic matter increased steadily from about 11% to over 25% at the core's upper transitional phase boundary. In Fiddlers Lake, a spike in organic matter content at a depth of 332 centimeters caused a jump from late-glacial values to 14%, and back down to 6%. Values continued to rise towards the upper boundary of the transitional unit until organic matter suddenly increased 23% between consecutive samples. This organic matter content peak at about 10,700 cal. years BP measured nearly 49%, the highest value recorded in both cores, and marked the upper boundary of the transitional phase.

Silt mineralogy results during the transitional phase did not reveal any trends. The majority of samples analyzed for clay mineralogy displayed weak clay peaks in both lakes (Figure 17). Both heavy mineral analysis samples from each lake encountered less than ten grains. The mineralogy analyses for the transitional phase of both lakes consistently lacked results. This may have been due to the increasing organic matter in the cores which affected clastic input. Increased physical or chemical weathering of the minerals may have also influenced sediment mineralogy.

Sand and silt contents for Fiddlers Lake and Louis Lake varied inversely during the transitional period. Following the late-glacial period, Louis Lake's sand values

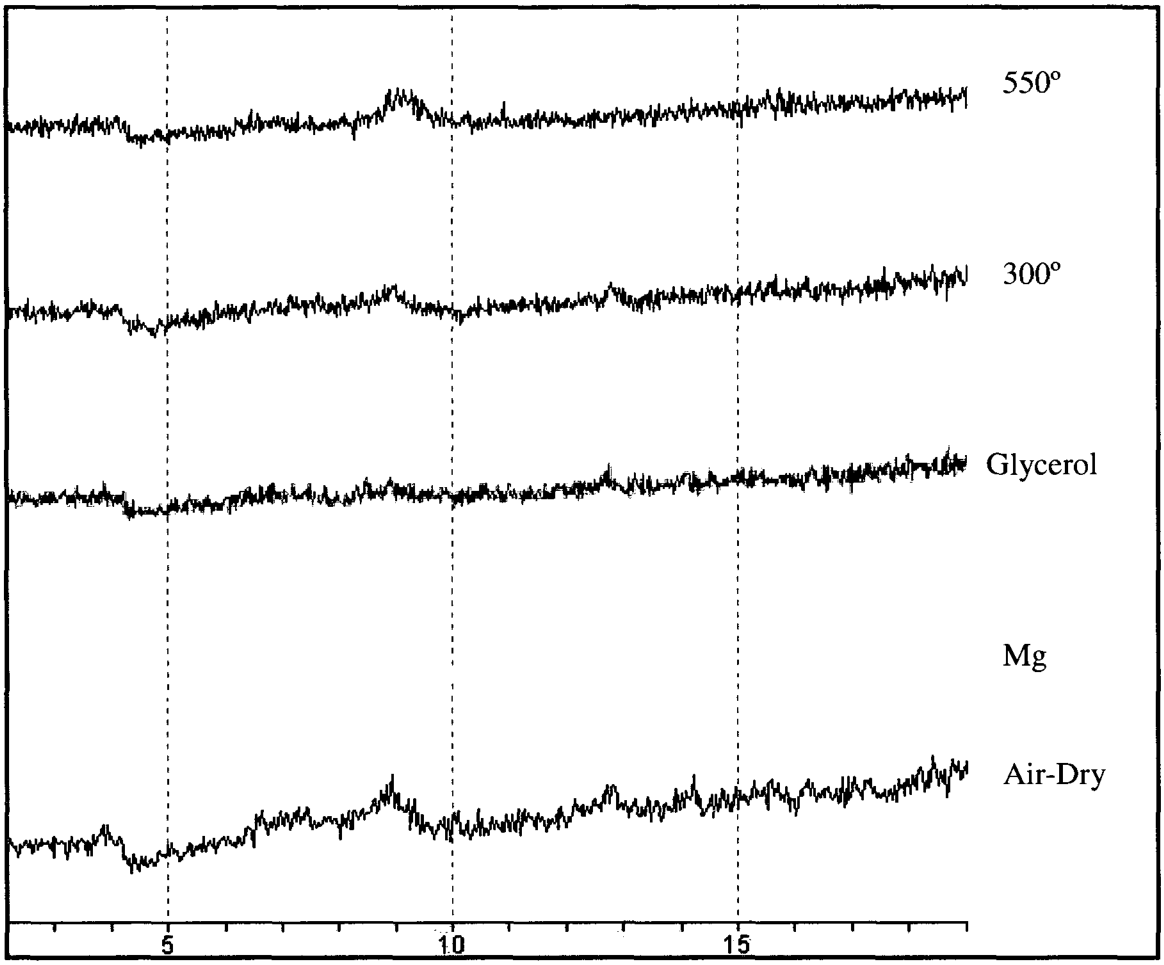


Figure 17: XRD peak signature of transitional sample (Fid_3L_74).

peaked near 43% while silt plummeted to around 50%. In Fiddlers Lake however, sand dropped from late-glacial values to around 6% while silt increased to approximately 80%. Sand content gradually increased before peaking at 43% at a depth of 252 centimeters. Before the upper boundary of the transitional period, both Fiddlers and Louis lakes' sand and silt content returned to early transitional-phase values.

The discrepancy in particle-size response during the transitional phase was the only point in the cores where the analyses were starkly conflicting. Organic matter was undoubtedly increasing in both cores at this time, yet Fiddlers Lake's sediment was silty while Louis Lake's was sandy. This may have been due to the differences in catchment area and hydrologic inputs between the basins. It is unknown whether there was a small glacier in the headwaters of Louis Lake and the present-day stream that feeds the lake is sizable (Figure 18). Fiddlers Lake's drainage basin is in effect the adjacent slopes above the lake and the predominant hydrologic input is likely groundwater flow (Figure 19). These differences may have caused the contradictory responses. The stream entering Louis Lake may have become established at this point and supplied the lake with coarser material from higher up in the basin. Or if there was a small glacier in Louis Lake's headwaters, it may have completely retreated by this time and its meltwaters carried sandy material down-valley to be deposited.

The Younger-Dryas cold interval took place between 12,900 and 11,700 cal. years BP and punctuated the termination of the last glacial period (Broecker et al., 2010). These dates occurred during the transitional phase in Fiddlers Lake (Figure 13) yet the lack of numeric dating precludes estimating where it occurred in Louis Lake.

The only apparent change or reversal in Fiddlers Lake analyses during this time period was organic matter content. Prior to this interval in the Fiddlers Lake core, organic matter had begun increasing. Organic matter contents leveled out at around 14% across forty centimeters (approximately 12,900-11,100 cal. years BP) then suddenly increased to over 38%. Sand and silt contents did not appear to be influenced during this interval, though briefly after 11,000 cal. years BP sand content recorded an increase while silt decreased before returning to pre-Younger-Dryas interval values (Figure 13).

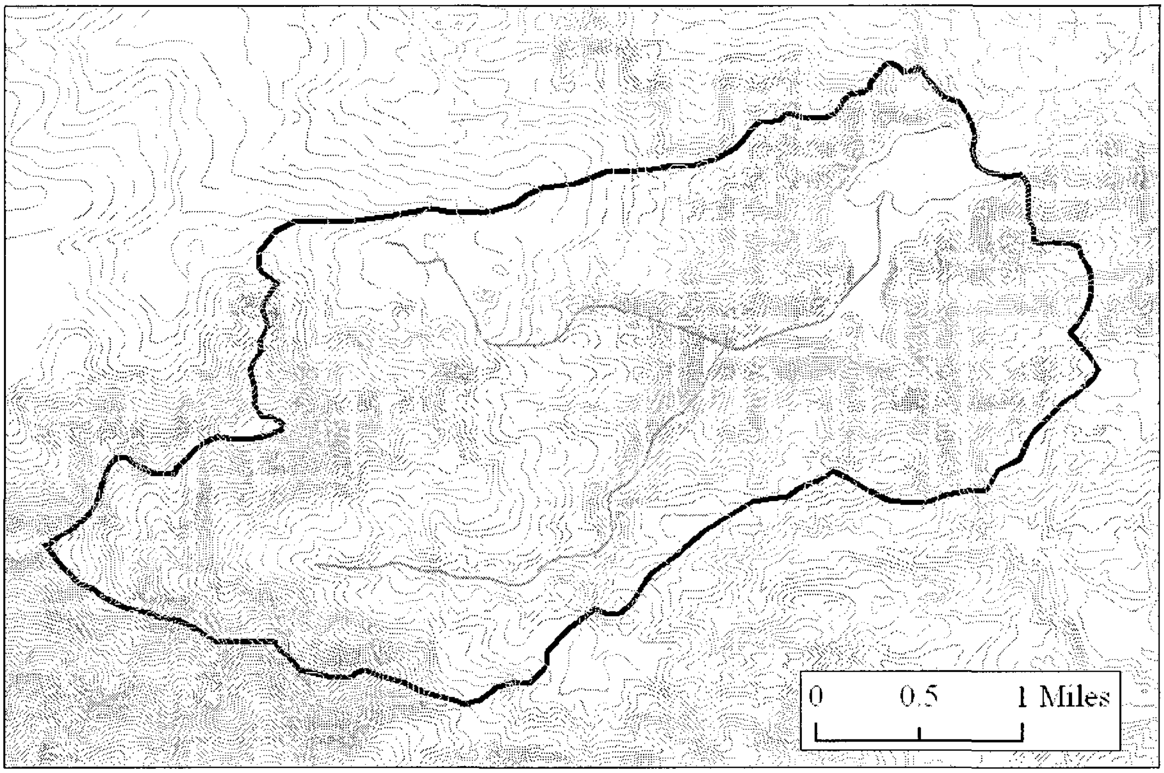


Figure 18: Louis Lake Basin. Contour interval is 10 meters. Modified from WyGISC (http://www.uwyo.edu/wygisc/) data.

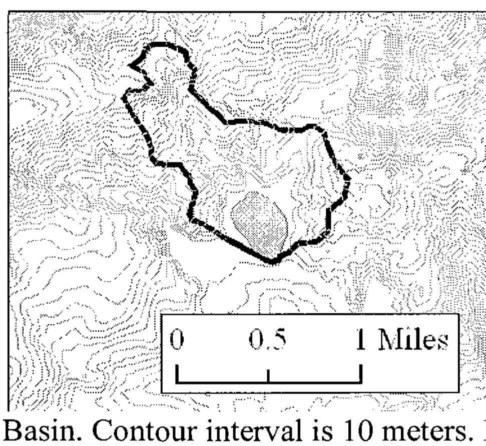


Figure 19: Fiddlers Lake Basin. Contour interval is 10 meters. Modified from WyGISC (http://www.uwyo.edu/wygisc/) data.

Though there was undoubtedly a cause for the organic matter plateau, this does not definitively verify a Younger-Dryas effect registered by Fiddlers Lake core. There was not a correlative response in Louis Lake's organic matter content as organic matter content increased without break during the transitional phase. Although the transitional period suggested the basins revealed slightly different responses in particle-size, it was assumed that Louis Lake would register an analogous effect to a large-scale, millennial-duration cold event.

Post-Glacial

Sediment deposited after approximately 10,700 cal. years BP was classified as post-glacial sediment. In the Louis Lake core, the post-glacial unit was approximately 260 centimeters thick. For Fiddlers Lake, the unit was approximately 150 centimeters thick, though this did not include 90 centimeters of material below the sediment-water interface not collected during retrieval. The most recent age for sediment sampled from the Fiddlers Lake core was approximately 3,030 cal. years BP. The estimated accumulation rate for the available sediment from Fiddlers Lake post-glacial period was 0.2 millimeters per year.

Post-glacial sediment was characterized by low clay content and inversely-variable silt and sand. Clay values for both cores' post-glacial period averaged approximately 7%. Silt was the dominant grain size, though two samples from Louis Lake contained higher sand than silt values and several others from the core recorded nearly equal sand-silt content. Silt and sand contents were variable for both lakes; Louis Lake recorded nearly cyclical fluctuations occurring every 40-50 centimeters (Figure 14).

Sedimentological characteristics of the post-glacial period exhibited a non-stable environment. Particle-size of both Fiddlers and Louis lakes demonstrated that the energy of hydrologic inputs varied throughout the post-glacial period. Fluctuations in sand content throughout the post-glacial were often significant and abrupt. In Louis Lake, pulses of coarse material appeared frequently and underscore the variability of environmental conditions during the Holocene. It was unknown what exactly caused these pulses and without dates it was impossible to estimate their duration. Unfortunately the sediment record for Fiddlers Lake did not extend to the present time, so it is unknown if it too showed cyclical variations similar to Louis Lake. The available post-glacial record for Fiddlers Lake certainly did not exhibit these pulses as frequently if the variations were cyclical.

Since Fiddlers Lake did not reveal as frequent (or as significant) variations, these pulses must have been local to the basin of Louis Lake. The size and topography of Louis Lake's basin likely contributed to these coarse sediment pulses (Figure 18). One possible explanation is that these cyclical pulses of coarse sediment were tied to variations in basin snowpack. It is expected the larger catchment area of Louis Lake's headwaters allowed for greater snowpack accumulation over time. When local or regional factors periodically caused the snowpack to melt, surface waters would transport greater coarse sediment loads to the lake. Also, increased stream flow energy or hydrologic inputs could possibly cause reworking or redistribution of coarser sediment within the lake.

Post-glacial sediment in Fiddlers Lake recorded the lowest average of silt minerals identified (less than 5). Louis Lake's silt mineralogy results identified more silt minerals than Fiddlers Lake, though there were no discernible trends. All clay mineralogy samples from Louis Lake displayed weak or no peaks (Figure 20) and no samples from Fiddlers Lake recorded any peaks.

Organic matter contents in both cores steadily declined toward their most recent values during the post-glacial period following the peak at the post-glacial/transitional boundary, though organic matter content was still significant. For Louis Lake, organic matter content gradually leveled out by the second half of the post-glacial sediment and

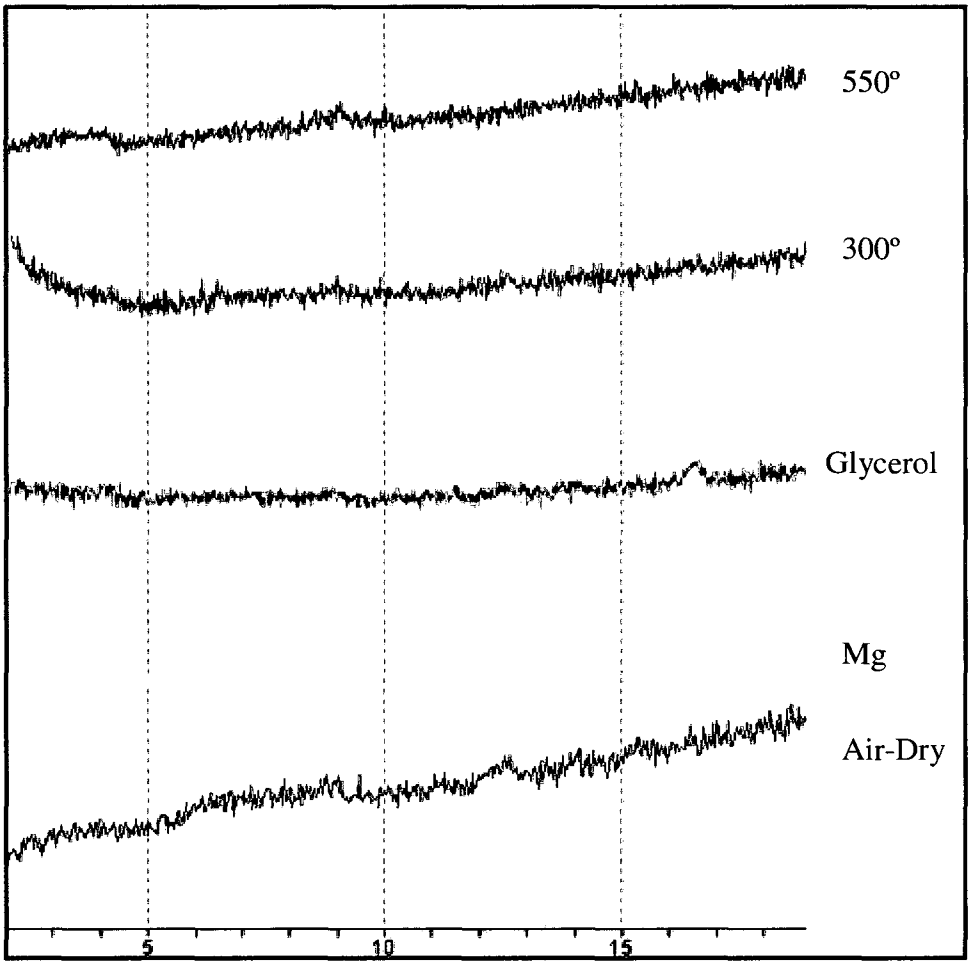


Figure 20: XRD peak signature of post-glacial sample (Lou_2L_60).

averaged 14% in the upper 140 centimeters of the core. Sediment in Fiddlers Lake declined in organic matter content to 24% at a depth of 142 centimeters. A peak in organic matter content between 5,000 and 4,000 cal. years BP reached 36%. The topmost sample in the Fiddlers Lake core measured 30%.

Although organic matter contents during the post-glacial phase declined and did not vary greatly, the sediment still contained considerable organic material. Post-glacial sediment in Louis Lake was classified as organic silt and Fiddlers Lake was described as fibrous, peaty organic sediment in the ICDs. Peat-like sediment suggests shallow water depths or bog-like conditions in Fiddlers Lake which may also account for the poor preservation and identification of silt and clay minerals. Abundant plant macro-fragments were observed in samples from Fiddlers Lake, suggesting biologic productivity in and around the lake was high. Considering both lake basins contain the same present-day land cover characteristics, it is likely the relatively small drainage basin and/or shallow water depth of Fiddlers Lake accounts for the higher accumulation of organic matter in the lake as biologic material would be supplied more directly.

Comparison with Regional Paleoclimate Records

Through multi-proxy research, a record of depositional and mineralogical characteristics for Fiddlers and Louis lakes was established. Particle-size analysis provided information on physical sedimentation characteristics, loss-on-ignition and organic matter content revealed local biologic production, and x-ray diffraction and heavy mineral analysis characterized the mineralogy of the sediment.

As discussed above, trends and patterns displayed in the results were used to define four distinct phases of sedimentological characteristics which corresponded to local environmental conditions at the time of deposition. Based on the data, general inferences about the local paleoclimate were made. Radiocarbon data allowed changes in Fiddlers Lake sediment characteristics to be numerically dated. These dates provided a way to compare the records of Fiddlers and Louis lakes to regional paleoclimate records.

Research in the Temple Lake Valley by Fall et al. (1995), Zielinski (1989), and Zeilinski and Davis (1987) and the Titcomb Basin by Gosse et al. (1999) showed similar responses to the late-Quaternary sedimentological records of Fiddlers and Louis lakes. Since the study by Fall et al. (1995) is the most recent and incorporated the previous work by Zielinski (1989) and Zielinski and Davis (1987), research in the Temple Lake Valley will hereafter reference Fall et al. (1995).

Although sediment analyzed by Fall et al. (1995) was deposited approximately 13,900 cal. years BP, it was presumed that warming by about 17,000 cal. years BP began the wasting of valley glaciers in the Wind River Range. This date is relatable to the 17,400 cal. years BP age assigned to the beginning of Fiddlers Lake's late-glacial period and when sand values increased in Fiddlers and Louis lakes. In the Titcomb Basin, Gosse et al. (1999) estimated deglaciation began approximately 15,900 cal. years BP, nearly synchronous with the 16,000 cal. years BP late-glacial/transitional boundary in the Fiddlers Lake core and the paleomagnetic shifts noted by Geiss et al. (2007; 2009).

Dahms (1993) found that eolian contribution to Wind River Range soils was significant, though not limited to late-glacial time. Mineralogic data from the present analyses only recorded strong eolian signals in full and late-glacial sediment mineralogy.

Pollen data from the Temple Lake Valley shows that vegetation responded quickly to changing environmental conditions between 15,000 and 11,400 cal. years BP, caused by the rapid retreat of alpine glaciers (Fall et al., 1995). Both studies from Bear Lake (Dean et al., 2006; Jimenez-Moreno et al., 2007) documented warmer, drier conditions in the early Holocene after approximately 12,000 cal. years BP. These dates roughly correspond to the increases in organic matter content in the Little Popo Agie Lakes during the transitional phase (Figures 13 and 14).

Organic material from the Temple Lake Valley cores increased continuously after 13,200 cal. years BP and reached its highest percentages between 11,400 and 9,300 cal. years BP (Fall et al., 1995). The organic matter content peak of 49% in Fiddlers Lake was dated approximately 10,700 cal. years BP.

Lynch (1998) found that pollen totals were greatest after approximately 10,700 cal. years BP in the northern Wind River Range. Whitlock et al. (1995) and Whitlock and Bartlein (1993) documented warm, dry conditions in Yellowstone between 10,700 and 5,700 cal. years BP. These findings agree with the above results from Fiddlers Lake, as organic matter averages were higher during the early post-glacial than previous phases.

Between 9,300 and 3,200 cal. years BP, deposited organic material declined in the Temple Lake Valley cores (Fall et al., 1995), as was seen in the Fiddlers and Louis lake cores after peaks at the transitional/post-glacial boundary. At approximately 5,600 cal.

years BP, Fall et al. (1995) observed a minor peak in organics which was attributed to warm, dry conditions. A considerable peak in Fiddlers Lake between 5,000 and 4,000 cal. years BP may be related, though there was no discernible peak in Louis Lake.

Changes in late-Holocene pollen assemblage from lakes in the northern Wind River Range (Lynch, 1998) were assumed to be a result of cooler temperatures after about 5,700 cal. years BP. Lynch (1998) attributed the cooler temperatures to orbital parameters causing a decrease in summer insolation. This would likely affect the organic matter content in the post-glacial sediment of Fiddlers and Louis lakes, though these values began declining prior to this time (Figures 13 and 14).

The Fiddlers and Louis lake cores supported the trends and patterns found in the paleoclimatic records throughout the Wind River Range. Radiocarbon ages allowed the paleolimnological responses of Fiddlers Lake to be numerically dated and these dates made possible the correlation to regional paleoclimatic records. Although Louis Lake was not able to be accurately dated, the responses to environmental conditions were analogous to Fiddlers Lake. The consistent responses between the paleolimnological record of the Little Popo Agie Basin lakes and the other Wind River Range paleoclimatic studies confirm that the sedimentological characteristics of Fiddlers and Louis lakes corroborated regional environmental conditions and changes.

Conclusions

The sedimentological record from Fiddlers and Louis lakes represents the longest, continuous limnological record in the Wind River Range. The cores were deposited as early as 20,000 cal. years BP and contain records of full-glacial conditions, a rarity for alpine lakes in the western United States.

Through multi-proxy research, a history of late-Quaternary depositional and mineralogical variability was established for Fiddlers and Louis lakes. The responses of paleolimnological indicators in both lakes verify four distinct periods of deposition: full-glacial, late-glacial, transitional and post-glacial. Sediment deposited during the full-glacial was silt-rich, lacked significant organic material and contained higher proportions of non-native silt and clay. The late-glacial phase was marked primarily by an increase in sand content. The transitional phase was identified by increasing organic matter content and variable sand and silt content. Post-glacial sediment was characterized by variable sand and silt, low clay values and decreasing organic matter content.

Radiocarbon ages from Fiddlers Lake provided numeric dating of the record which constrained the timing of environmental changes in the Little Popo Agie Basin. The ability to date the sediment record also provided a way to compare the sedimentological records from this research to regional paleoclimatic research. Previous research in the Wind River Range corroborated the environmental responses of Fiddlers and Louis lakes.

Limitations

Samples for radiocarbon dates were only taken from Fiddlers Lake core and no deeper than a depth of about 340 centimeters (less than halfway down the core). Consequently, the date of earliest deposition of sediment is not precisely known or well-constrained. Fiddlers Lake sediment younger than approximately 15,700 cal. years BP was too weakly magnetized to correlate to Louis Lake and sedimentological changes in Louis Lake could not be chronologically constrained with any confidence.

Several samples from Fiddlers Lake's post-glacial phase were not analyzed for silt and clay mineralogy, as there was no sample to analyze. Samples for the XRD were leftovers from the PSA and since the Fiddlers Lake post-glacial sediment had considerable organic content, the removal of organics prior to the PSA analysis significantly diminished the size of useable sample. If larger samples were taken from cores, fresh samples could have been used for this analysis ensuring sufficient sample for each method.

The heavy mineral analyses offered only two valid samples, therefore no discernible trends could be correlated to environmental conditions or phases. This may be due to the use of too small of samples since leftover sediment from the previous analyses was all that was available, as mentioned above.

It is unknown whether the valley above Louis Lake was glaciated during the Pleistocene. If physical geomorphic evidence in the valley were observed, more detailed sedimentological interpretations could possibly be developed.

Suggestions for Future Research

To further refine the late-Quaternary paleoclimate record of the Wind River Range, more paleolimnological research must be undertaken. This entails coring and analyzing sediment from a variety of locations to fill in the spatial and temporal gaps. The wide distribution and diverse settings of lakes offer the potential to record regional variations of environmental change. A better understanding of the processes and effects of paleoclimate will be gained as additional paleoclimate records are established.

Beyond coring and analyzing sediment from additional lakes, there are a variety of paleolimnological methods that were not employed for this study. Pollen and diatom data are valuable indicators of environmental conditions, while charcoal analysis may reveal temporal patterns of forest fires or drought. The extent of paleolimnological analyses vary depending on the application and scope of the study and capability of the researcher.

To improve understanding of paleoclimatic conditions in the Little Popo Agie Basin and Wind River Range, additional research must be undertaken to refine the late-Quaternary paleoclimatic record. Lake sediment offers abundant data making limnological studies a resourceful approach to paleoclimatic research. Though alpine lakes containing sediment deposited before deglaciation have not been widely studied in the Wind River Range, these lakes hold the potential to shed light on full-glacial conditions and climatic transitions.

REFERENCES

Anderson, D.E., Goudie, A.S., & Parker, A.G. (2007). *Global environments through the Quaternary.* New York, NY: Oxford University Press.

Armour, J., Fawcett, P.J., & Geissman, J.W. (2002). 15 k.y. paleoclimatic and glacial record from northern New Mexico. *Geology, 30*(8), 723-726.

Battarbee, R.W. (2000) Paleolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews, 19,* 107-124.

Bjorck, S., & Wohlfarth, B. (2001). ^{14}C chronostratigraphic techniques in paleolimnology. In W.M. Last & J.P. Smol (Eds.), *Tracking environmental change. Vol. 1: Basin analysis, coring, and chronological techniques* (pp. 205-245). Dordrecht, Netherlands: Kluwer Academics.

Bradley, R.S. (1999). *Paleoclimatology: Reconstructing climates of the Quaternary.* San Diego, CA: Academic Press.

Broecker, W.S., Denton, G.H., Edwards, R.L., Cheng, H., Alley, R.B., & Putnam, A.E. (2010). Putting the Younger Dryas cold event into context. *Quaternary Science Reviews, 29,* 1078-1081.

Brunelle, A., Whitlock, C., Bartlein, P., & Kipfmueller, K. (2005). Holocene fire and vegetation along environmental gradients in the northern Rocky Mountains. *Quaternary Science Reviews, 24,* 2281-2300.

Carver, R.E. (ed.). (1971) *Procedures in sedimentary petrology.* New York, NY: Wiley-Interscience.

Case, J.C., Arneson, C.S., & Hallbe, L.L. (1998). [Spatial dataset]. *Wyoming surficial geology.* Available from Wyoming Geographic Information Science Center http://www.uwyo.edu/wygisc

Chao, G.Y. (1969). 2-theta (Cu) table for common minerals. *Geological paper 69-2.* Carleton University, Ottawa, Canada.

Cohen, A.S. (2003). *Paleolimnology: The history and evolution of lake systems.* New York, NY: Oxford University Press.

Corbett, L.B., & Munroe, J.S. (2010). Investigating the influence of hydrogeomorphic setting on the response of lake sedimentation to climatic changes in the Uinta Mountains, Utah, USA. *Journal of Paleolimnology*. doi:10.1007/s10933-009-9405-9.

Dahms, D.E. (1991). *Eolian sedimentation and soil development on moraine catenas of the Wind River Mountains, west central Wyoming.* Unpublished doctoral dissertation, University of Kansas, Lawrence.

Dahms, D.E. (1993). Mineralogical evidence for eolian contribution to soils of late Quaternary moraines, Wind River Mountains, Wyoming, USA. *Geoderma, 59,* 175-196.

Dahms, D.E. (2002). Glacial stratigraphy of Stough Creek Basin, Wind River Range, Wyoming. *Geomorphology, 42,* 59-83.

Dean, W., Rosenbaum, J., Skipp, G., Colman, S., Forester, R., Liu, A., Simmons, K., & Bischoff, J. (2006). Unusual Holocene and late Pleistocene carbonate sedimentation in Bear Lake, Utah and Idaho, USA. *Sedimentary Geology, 185*(1-2), 93-112.

Downs, R.T., & Hall-Wallace, M. (2003). [Dataset] *American mineralogist crystal structure database.* Retrieved February 22, 2010, from http://rruff.geo.arizona.edu/AMS/all_minerals.php

Fall, P.L., Davis, P.T., & Zielinski, G.A. (1995). Late Quaternary vegetation and climate of the Wind River Range, Wyoming. *Quaternary Research, 43,* 393-404.

Fritz, S.C. (1996). Paleolimnological records of climatic change in North America. *Limnology and Oceanography, 41*(5), 882-889.

Frost, B.R., Frost, C.D., Hulsebosch, T.P., & Swapp, S.M. (2000). Origin of the charnockites of the Louis Lake Batholith, Wind River Range, Wyoming. *Journal of Petrology, 41*(12), 1759-1776.

Geiss, C. (2010). *Wyoming lakes magnetic properties* [dataset]. Received by personal communication February 15, 2010.

Geiss, C., Dorale, J., & Dahms, D. (2007) *A rockmagnetic and palaeomagnetic record of two glacial lakes in the Wind River Range, Wyoming, U.S.A.* American Geophysical Union, Fall Meeting 2007, abstract #GP53B-1216.

Geiss, C., Dorale, J., & Dahms, D. (2009). Rock-magnetic record of two glacial lakes reflects history of glacial retreat and landscape stabilization in the eastern Wind River Range at the Pleistocene-Holocene transition. *GSA Abs. Prog., 41*(7).

Gosse, J., Davis, P.T., Burr, G., Jull, A.J.T., Bozarth, S., Sorenson, C., Klein, J., Lawn, B., Dahms, D. (1999). Late Pleistocene/Holocene glacial and paleoclimatic history of Titcomb Basin, Wind River Range, Wyoming based on lake sediments and cosmogenic nuclide dating. *GSA Abs. Prog., 31*(7), A-56.

Heinrich, E.W. (1965). *Microscopic identification of minerals.* New York, NY: McGraw-Hill.

Jimenez-Moreno, G., Anderson, R.S., & Fawcett, P.J. (2007). Orbital- and millennial-scale vegetations and climate changes of the past 225 ka from Bear Lake, Utah-Idaho (USA). *Quaternary Science Reviews, 26,* 1713-1724.

Kerr, P.F. (1959). *Optical mineralogy.* New York, NY: McGraw-Hill.

Legg, T.E., & Baker, R.G. (1980). Palynology of Pinedale sediments, Devlins Park, Boulder County, Colorado. *Arctic and Alpine Research, 12*(3), 319-333.

Last, W.M. (2001). Textural analysis of lake sediments. In W.M. Last & J.P. Smol (Eds.), *Tracking environmental change. Vol. 2: Physical and geochemical methods* (pp. 41-81). Dordrecht, Netherlands: Kluwer Academics.

Last, W.M., & Smol, J.P. (2001). An introduction to basin analysis, coring, and chronological techniques used in paleolimnology. In W.M. Last & J.P. Smol (Eds.), *Tracking environmental change. Vol. 1: Basin analysis, coring, and chronological techniques* (pp. 1-5). Dordrecht, Netherlands: Kluwer Academics.

Lynch, E.A. (1998). Origin of a park-forest vegetation mosaic in the Wind River Range, Wyoming. *Ecology, 79*(4), 1320-1338.

MacLeod, D.M., Osborn, G., Spooner, I. (2006). A record of post-glacial moraine deposition and tephra stratigraphy from Otokomi Lake, Rose Basin, Glacier National Park, Montana. *Canadian Journal of Earth Sciences, Vol. 43*, 447-460.

Materials Data Incorporated (2005). *Jade (version 7.1)* [software]. Livermore, CA.

Mazzucchi, D., Spooner, I.S., Gilbert, R., & Osborn, G. (2003). Reconstruction of Holocene climate change using multiproxy analysis of sediments from Pyramid Lake, British Columbia, Canada. *Arctic, Antarctic, and Alpine Research, 35*(4), 520-529.

Millspaugh, S.H., Whitlock, C., & Bartlein, P.J. (2000). Variations in fire frequency and climate over the past 17,000 yr in central Yellowstone National Park. *Geology, 28*(3), 211-214.

Milner, H.B. (1962). *Sedimentary petrography.* London: Allen & Unwin.

Myrbo, A. (2004). *Standard Operating Procedures series – Subsampling lake sediment cores.* Retrieved January 20, 2010, from http://lrc.geo.umn.edu/subsampling.pdf

Myrbo, A. (2005). *Standard Operating Procedures series – Initial Core Description (ICD): Overview.* Retrieved January 20, 2010, from http://lrc.geo.umn.edu/icd.pdf

Poppe, L.J., & Eliason, A.H. (2008). *SEDPLOT: Sediment classification and plotting* [software]. Available from http://woodshole.er.usgs.gov/software/sediment-software.html

Reasoner, M.A., & Jodry, M.A. (2000). Rapid response of alpine timberline vegetation to the Younger Dryas climate oscillation in the Colorado Rocky Mountains, USA. *Geology, 28*(1), 51-54.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Bronk Ramsey, C., Buck, C.E., Burr, G.S., Edwards, R.L., Friedrich, M., Grootes, P.M., Guilderson, T.P., Hajdas, I., Heaton, T.J., Hogg, A.G., Hughen, K.A., Kaiser, K.F., Kromer, B., McCormac, F.G., Manning, S.W., Reimer, R.W., Richards, D.A., Southon, J.R., Talamo, S., Turney, C.S.M., van der Plicht, J., & Weyhenmeyer, C.E. (2009). [Dataset] *IntCal09.14c.* Retrieved February 15, 2010, from http://www.radiocarbon.org/IntCal09%20files/intcal09.14c

Sapota, T., Aldahan, A., & Al-Aasm, I.S. (2005). Sedimentary facies and climate control on formation of vivianite and siderite microconcretions in sediments of Lake Baikal, Siberia. *Journal of Paleolimnology, 36*(3), 245-257.

Scholle, P.A. (1981). *A color illustrated guide to constituents, textures, cements, and porosities of sandstones and associated rocks (Memoir 28).* Tulsa, OK: American Association of Petroleum Geologists.

Schnurrenberger, D., Russell, J., & Kelts, K. (2003). Classification of lacustrine sediments based on sedimentary components. *Journal of Paleolimnology, 29,* 141-154.

Shepard, F.P. (1954). Nomenclature based on sand-silt-clay ratios. *Journal of Sedimentary Petrology, 24*(3), 151-158.

Stuvier, M., & Reimer, P.J. (2010). *CALIB 6.0.1* [software]. Available from http://www.calib.org

U.S. Geological Survey. (2003). [Spatial dataset]. *National land cover database 2001.* Available from http://seamless.usgs.gov/

Whitlock, C., & Bartlein, P.J. (1993). Spatial variations of Holocene climatic change in the Yellowstone Region. *Quaternary Research, 39,* 231-239.

Whitlock, C., Bartlein, P.J., & Van Norman, K.J. (1995). Stability of Holocene climate regimes in the Yellowstone region. *Quaternary Research, 43,* 433-436.

Woodhouse, C.A., & Overpeck, J.T. (1998). 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society, 79*(12), 2693-2714.

Zielinski, G.A. (1989). Lacustrine sediment evidence opposing Holocene rock glacier activity in the Temple Lake Valley, Wind River Range, Wyoming, U.S.A. *Arctic and Alpine Research, 21*(1), 22-33.

Zielinski, G.A., & Davis, P.T. (1987). Late Pleistocene age of the type Temple Lake moraine, Wind River Range, Wyoming, U.S.A. *Geographie physique et Quaternaire, 41*(3), 397-401.

Zolitschka, B., Mingram, J., Gaast, S., Jansen, J.H., & Nauman, R. (2001). Sediment logging techniques. In W.M. Last & J.P. Smol (Eds.), *Tracking environmental change. Vol. 1: Basin analysis, coring, and chronological techniques* (pp. 137-153). Dordrecht, Netherlands: Kluwer Academics.

APPENDIX A

PARTICLE SIZE ANALYSIS

Fiddlers Lake Particle Size Results

Sample Name	Depth (cm)	% Sand (>50um)	% Silt (2-50um)	% Clay (<2um)	% Coarse Silt (20-50um)	% Fine Silt (2-20um)
Fid_1B_14	92	12.90	80.05	7.05	28.55	51.50
Fid_1B_24	102	15.20	78.31	6.49	29.90	48.41
Fid_1B_34	112	13.00	79.89	7.11	29.90	49.99
Fid_1B_44	122	20.20	73.82	5.98	29.50	44.32
Fid_1B_54	132	9.90	82.47	7.63	27.90	54.57
Fid_1B_64	142	5.85	85.94	8.21	26.55	59.39
Fid_1B_74	152	8.20	84.36	7.44	30.50	53.86
Fid_1B_84	162	4.30	86.38	9.32	28.00	58.38
Fid_1B_94	172	3.05	88.78	8.17	31.20	57.58
Fid_3L_04	182	23.40	71.19	5.41	2.20	68.99
Fid_3L_14	192	23.60	71.08	5.32	29.10	41.98
Fid_3L_24	202	27.20	67.59	5.21	27.50	40.09
Fid_3L_34	212	20.60	73.93	5.47	30.40	43.53
Fid_3L_44	222	20.00	74.74	5.26	31.30	43.44
Fid_3L_54	232	19.40	73.75	6.85	27.60	46.15
Fid_3L_64	242	17.20	77.19	5.61	31.70	45.49
Fid_3L_70	248	28.00	67.55	4.45	32.10	35.45
Fid_3L_74	252	42.50	53.19	4.31	28.00	25.19
Fid_3L_84	262	25.60	67.71	6.69	26.80	40.91
Fid_3L_94	272	17.80	74.04	8.16	25.60	48.44
Fid_4L_17	292	15.00	72.05	12.95	28.50	43.55
Fid_4L_27	302	6.00	79.80	14.20	28.20	51.60
Fid_4L_37	312	3.45	80.50	16.05	25.15	55.35
Fid_4L_47	322	10.75	77.20	12.05	28.90	48.30
Fid_4L_57	332	10.30	80.90	8.80	26.05	54.85
Fid_4L_67	342	29.40	60.05	10.55	27.50	32.55
Fid_4L_77	352	20.55	65.95	13.50	25.55	40.40
Fid_4L_87	362	24.05	63.35	12.60	23.70	39.65
Fid_4L_97	372	32.55	57.20	10.25	22.60	34.60

(table continues)

Sample Name	Depth (cm)	% Sand (>50um)	% Silt (2-50um)	% Clay (<2um)	% Coarse Silt (20-50um)	% Fine Silt (2-20um)
Fid_5L_12	383	16.20	71.15	12.65	27.80	43.35
Fid_5L_32	403	19.10	69.55	11.35	27.10	42.45
Fid_5L_52	423	11.55	73.70	14.75	23.80	49.90
Fid_5L_72	443	17.85	69.30	12.85	25.50	43.80
Fid_5L_92	463	17.15	69.55	13.30	25.65	43.90
Fid_6L_21	489	13.15	72.25	14.60	23.10	49.15
Fid_6L_41	509	13.90	69.70	16.40	19.20	50.50
Fid_6L_61	529	12.90	70.40	16.70	18.90	51.50
Fid_6L_81	549	14.50	69.20	16.30	18.65	50.55
Fid_7L_02	569	12.30	71.75	15.95	20.25	51.50
Fid_7L_22	589	12.60	72.10	15.30	20.15	51.95
Fid_7L_32	599	13.15	71.17	15.69	15.80	55.37
Fid_7L_42	609	3.03	83.17	13.80	25.63	57.53
Fid_7L_62	629	8.45	74.95	16.60	20.95	54.00
Fid_7L_82	649	8.55	74.85	16.60	19.70	55.15
Fid_8L_27	670	6.35	76.65	17.00	18.25	58.40
Fid_8L_47	690	7.65	74.55	17.80	17.35	57.20
Fid_8L_67	710	7.65	72.95	19.40	18.95	54.00
Fid_8L_87	730	6.05	77.75	16.20	18.65	59.10
Fid_9L_09	750	4.70	78.00	17.30	17.15	60.85
Fid_9L_29	770	7.20	76.45	16.35	16.15	60.30
Fid_9L_49	790	7.75	75.60	16.65	16.65	58.95
Fid_9L_69	810	8.90	75.50	15.60	18.50	57.00
Fid_9L_89	830	8.00	75.70	16.30	16.25	59.45
Fid_9L_95	836	16.20	70.45	13.35	20.50	49.95
Fid_9L_97	838	21.60	66.70	11.70	20.90	45.80

Louis Lake Particle Size Results

Sample Name	Depth (cm)	% Sand (>50um)	% Silt (2-50um)	% Clay (<2um)	% Coarse Silt (20-50um)	% Fine Silt (2-20um)
Lou_1L_70	7	6.75	81.65	11.60	29.50	52.15
Lou_1L_80	17	38.50	56.20	5.30	27.70	28.50
Lou_1L_90	27	16.95	76.27	6.78	34.45	41.82
Lou_2L_10	37	36.05	58.39	5.57	29.35	29.04
Lou_2L_20	47	42.50	52.13	5.37	24.80	27.33
Lou_2L_30	57	50.00	45.59	4.41	23.25	22.34
Lou_2L_40	67	46.25	49.08	4.67	24.75	24.33
Lou_2L_50	77	11.10	80.11	8.80	30.70	49.41
Lou_2L_60	87	40.40	54.62	4.99	28.55	26.07
Lou_2L_70	97	36.95	57.80	5.26	29.05	28.75
Lou_2L_80	107	38.60	56.61	4.80	30.55	26.06
Lou_2L_90	117	46.40	47.70	5.90	19.70	28.00
Lou_2L_100	127	45.75	48.50	5.75	21.00	27.50
Lou_3L_10	132	23.33	68.63	8.03	28.27	40.37
Lou_3L_20	142	26.50	65.83	7.68	28.30	37.53
Lou_3L_30	152	43.35	52.64	4.02	31.00	21.64
Lou_3L_40	162	31.65	61.48	6.87	25.30	36.18
Lou_3L_50	172	29.90	64.37	5.73	28.30	36.07
Lou_3L_60	182	37.25	56.55	6.21	23.70	32.85
Lou_3L_70	192	13.35	78.80	7.86	22.60	56.20
Lou_3L_80	202	42.55	51.58	5.87	21.15	30.43
Lou_3L_90	212	45.00	49.38	5.62	20.55	28.83
Lou_4L_02	222	26.50	64.90	8.61	25.20	39.70
Lou_4L_12	232	51.40	43.45	5.16	18.60	24.85
Lou_4L_22	242	10.85	79.34	9.82	26.10	53.24
Lou_4L_32	252	11.85	77.30	10.85	26.30	51.00
Lou_4L_42	262	25.20	67.59	7.21	27.65	39.94
Lou_4L_52	272	27.45	66.27	6.29	25.55	40.72
Lou_4L_62	282	24.90	68.84	6.26	27.20	41.64
Lou_4L_72	292	39.20	55.95	4.86	26.60	29.35
Lou_4L_82	302	41.87	52.03	6.10	21.30	30.73
Lou_4L_92	312	42.80	50.99	6.21	21.80	29.19
Lou_4L_102	322	41.15	52.49	6.36	21.90	30.59
Lou_5L_11	332	19.45	70.67	9.89	23.60	47.07
Lou_5L_21	342	22.05	68.67	9.28	24.60	44.07

(table continues)

Sample Name	Depth (cm)	% Sand (>50um)	% Silt (2-50um)	% Clay (<2um)	% Coarse Silt (20-50um)	% Fine Silt (2-20um)
Lou_5L_31	352	16.05	68.15	15.80	21.80	46.35
Lou_5L_41	362	18.80	66.35	14.85	22.20	44.15
Lou_5L_51	372	24.50	62.60	12.90	22.20	40.40
Lou_5L_61	382	12.80	72.40	14.80	22.95	49.45
Lou_5L_71	392	17.95	70.50	11.55	26.50	44.00
Lou_5L_81	402	14.05	72.30	13.65	26.25	46.05
Lou_5L_91	412	13.25	73.80	12.95	25.65	48.15
Lou_6L_09	422	10.25	76.25	13.50	26.20	50.05
Lou_6L_29	442	10.25	76.00	13.75	25.65	50.35
Lou_6L_49	462	9.85	77.30	12.85	28.15	49.15
Lou_6L_69	482	7.35	79.90	12.75	28.95	50.95
Lou_6L_89	502	2.25	83.80	13.95	27.85	55.95
Lou_7L_13	522	4.35	82.30	13.35	29.20	53.10
Lou_7L_33	542	5.70	80.55	13.75	28.10	52.45
Lou_7L_53	562	3.50	81.35	15.15	25.45	55.90
Lou_7L_73	582	4.70	80.20	15.10	25.55	54.65
Lou_7L_93	602	4.70	80.50	14.80	25.30	55.20
Lou_8L_59	652	2.85	82.05	15.10	24.45	57.60
Lou_8L_79	672	5.70	80.10	14.20	25.60	54.50
Lou_8L_99	692	7.15	78.55	14.30	23.05	55.50
Lou_9L_30	715	6.55	78.00	15.45	22.45	55.55
Lou_9L_50	735	4.15	81.30	14.55	24.70	56.60
Lou_9L_70	755	2.40	81.30	16.30	22.25	59.05
Lou_9L_90	775	5.35	80.25	14.40	26.15	54.10
Lou_10L_26	793	5.45	80.00	14.55	23.60	56.40
Lou_10L_46	813	5.80	79.85	14.35	22.60	57.25
Lou_10L_66	833	3.05	81.95	15.00	21.80	60.15
Lou_10L_86	853	3.15	81.20	15.65	20.40	60.80
Lou_11L_31	873	3.60	80.65	15.75	22.45	58.20
Lou_11L_51	893	1.65	82.35	16.00	21.10	61.25
Lou_11L_71	913	4.10	80.70	15.20	22.70	58.00
Lou_11L_91	933	2.50	82.35	15.15	21.15	61.20

APPENDIX B

X-RAY DIFFRACTION

Fiddlers Lake Clay Mineralogy Results

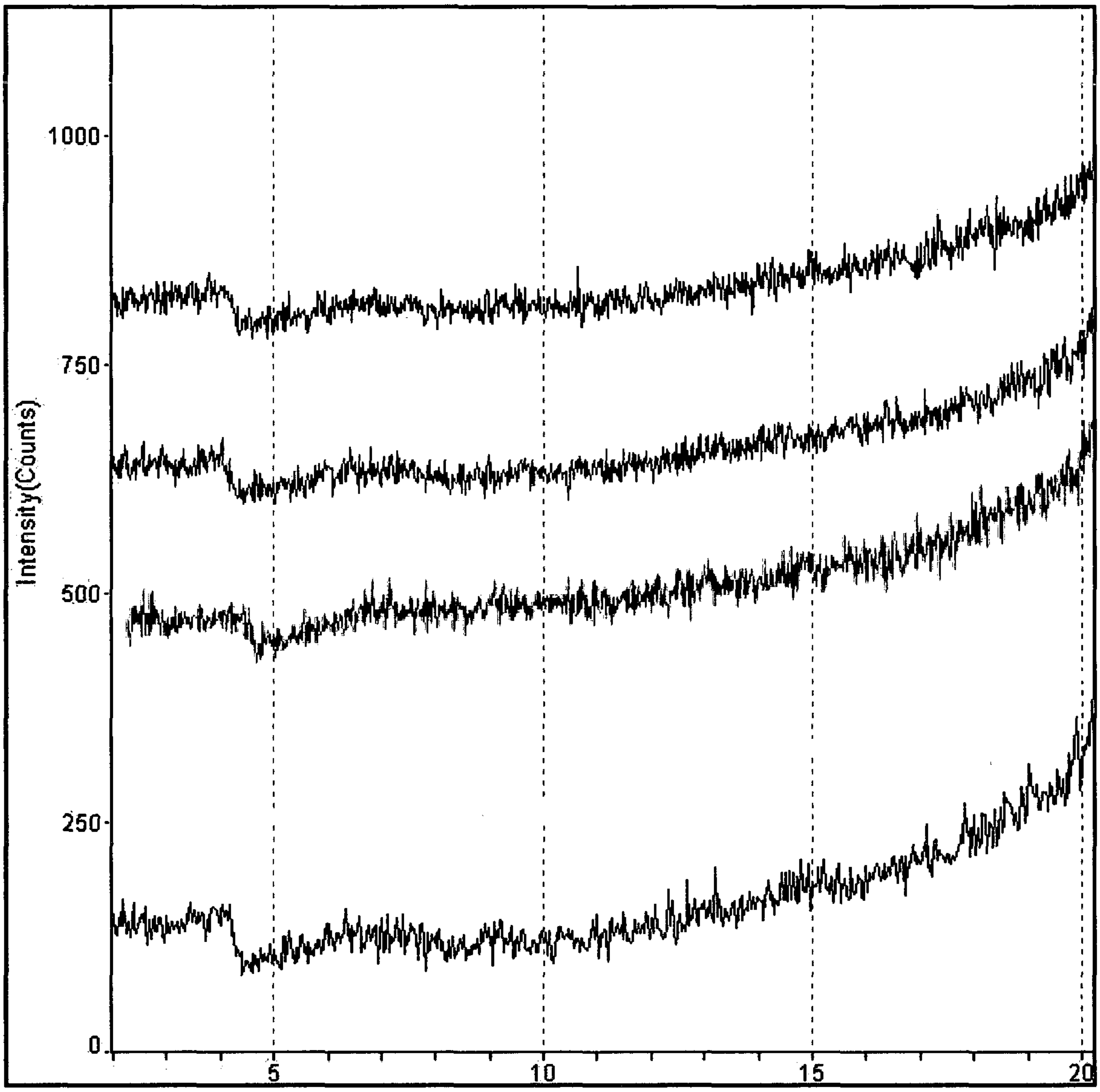
Sample	Lith. Unit	Phase	Vermiculite	Chlorite	Kaolinite	Smectite
Fid_1B_14	1	Post-Glacial				
Fid_3L_14	1	Post-Glacial				
Fid_3L_34	1	Post-Glacial				
Fid_3L_44	1	Post-Glacial				
Fid_3L_54	1	Post-Glacial				
Fid_3L_70	1	Transitional			weak kao	
Fid_3L_74	2	Transitional	weak verm		weak kao	
Fid_3L_84	2	Transitional	weak verm		weak kao	
Fid_3L_94	2	Transitional			weak kao	
Fid_4L_17	2	Transitional				
Fid_4L_27	3	Transitional			weak kao	
Fid_4L_37	3	Transitional			weak kao	
Fid_4L_47	3	Transitional			weak kao	
Fid_4L_57	3	Transitional	verm	weak chl	weak kao	
Fid_4L_67	3	Late-Glacial	weak verm		kao	
Fid_4L_77	4	Late-Glacial			weak kao	
Fid_4L_87	4	Late-Glacial	weak verm		kao	
Fid_4L_97	4	Late-Glacial	verm	weak chl	kao	smec
Fid_5L_12	4	Full-Glacial				
Fid_5L_32	4	Full-Glacial	verm	weak chl	kao	
Fid_5L_52	4	Full-Glacial			kao	
Fid_5L_72	4	Full-Glacial	verm	weak chl	kao	smec
Fid_5L_92	4	Full-Glacial	verm		kao	smec
Fid_6L_21	4	Full-Glacial	verm	weak chl	kao	smec
Fid_6L_41	4	Full-Glacial			kao	
Fid_6L_61	4	Full-Glacial	verm	weak chl	kao	smec
Fid_6L_81	4	Full-Glacial			kao	
Fid_7L_02	4	Full-Glacial	weak verm		kao	
Fid_7L_22	4	Full-Glacial	verm	weak chl	kao	smec
Fid_7L_32	4	Full-Glacial	verm	weak chl	kao	
Fid_7L_42	4	Full-Glacial			kao	
Fid_7L_62	4	Full-Glacial	verm	weak chl	kao	smec

(table continues)

Sample	Lith. Unit	Phase	Vermiculite	Chlorite	Kaolinite	Smectite
Fid_7L_82	4	Full-Glacial	weak verm	weak chl	kao	
Fid_8L_27	4	Full-Glacial		chl	kao	
Fid_8L_47	4	Full-Glacial			kao	
Fid_8L_67	4	Full-Glacial	verm		kao	
Fid_8L_87	4	Full-Glacial	weak verm		kao	
Fid_9L_09	4	Full-Glacial			kao	
Fid_9L_29	4	Full-Glacial		weak chl	kao	
Fid_9L_49	4	Full-Glacial	verm	chl	kao	smec
Fid_9L_69	4	Full-Glacial	verm	chl	kao	smec
Fid_9L_89	4	Full-Glacial	verm	chl	kao	smec
Fid_9L_95	4	Full-Glacial	verm	chl	kao	smec
Fid_9L_97	5	Full-Glacial	verm		kao	

Fiddlers Lake Clay Peak Traces

Traces are stacked vertically from bottom to top in order of successive pretreatment: air-dry, magnesium-chloride, glycerol, 300°C and 550°C.



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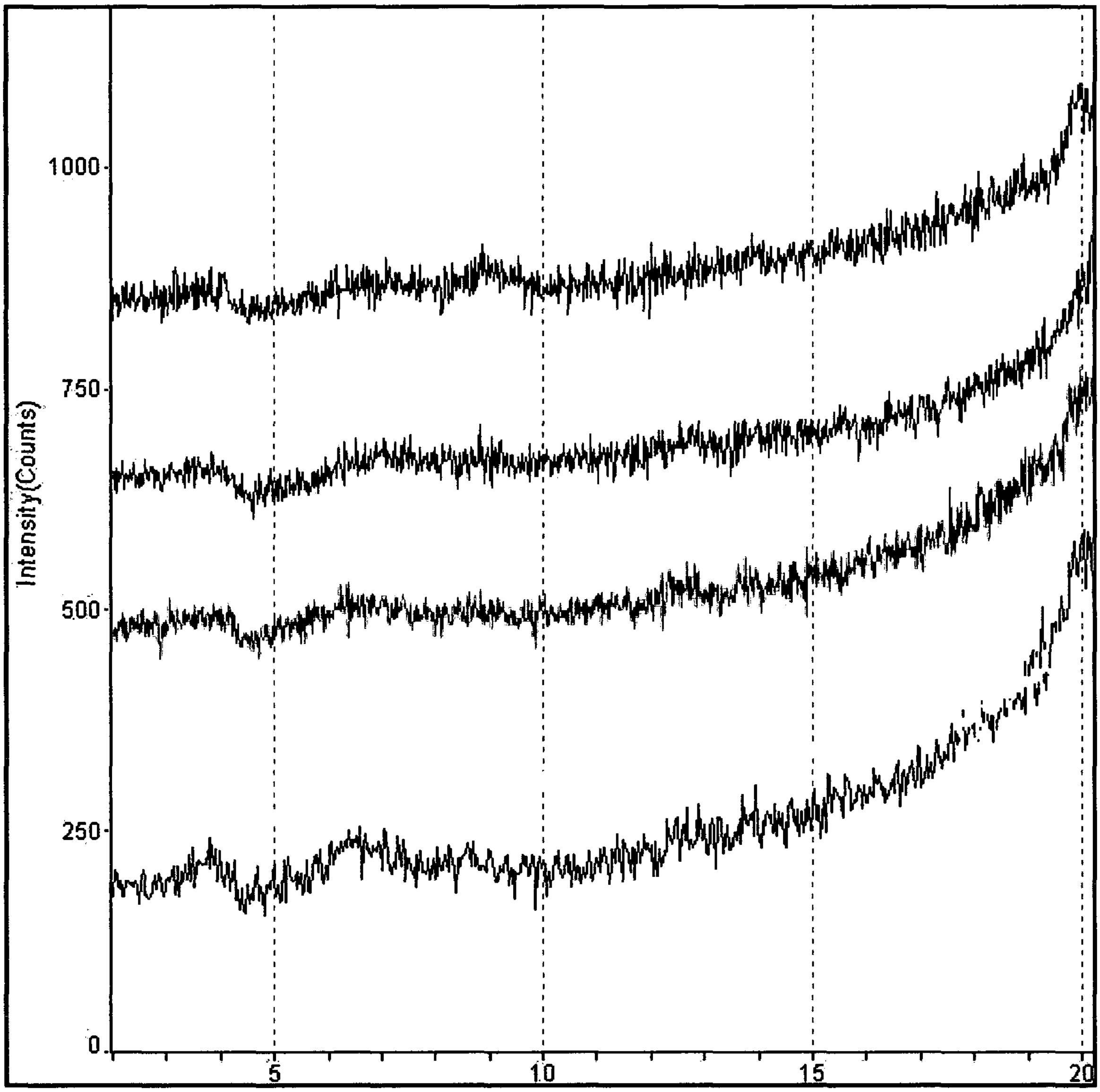

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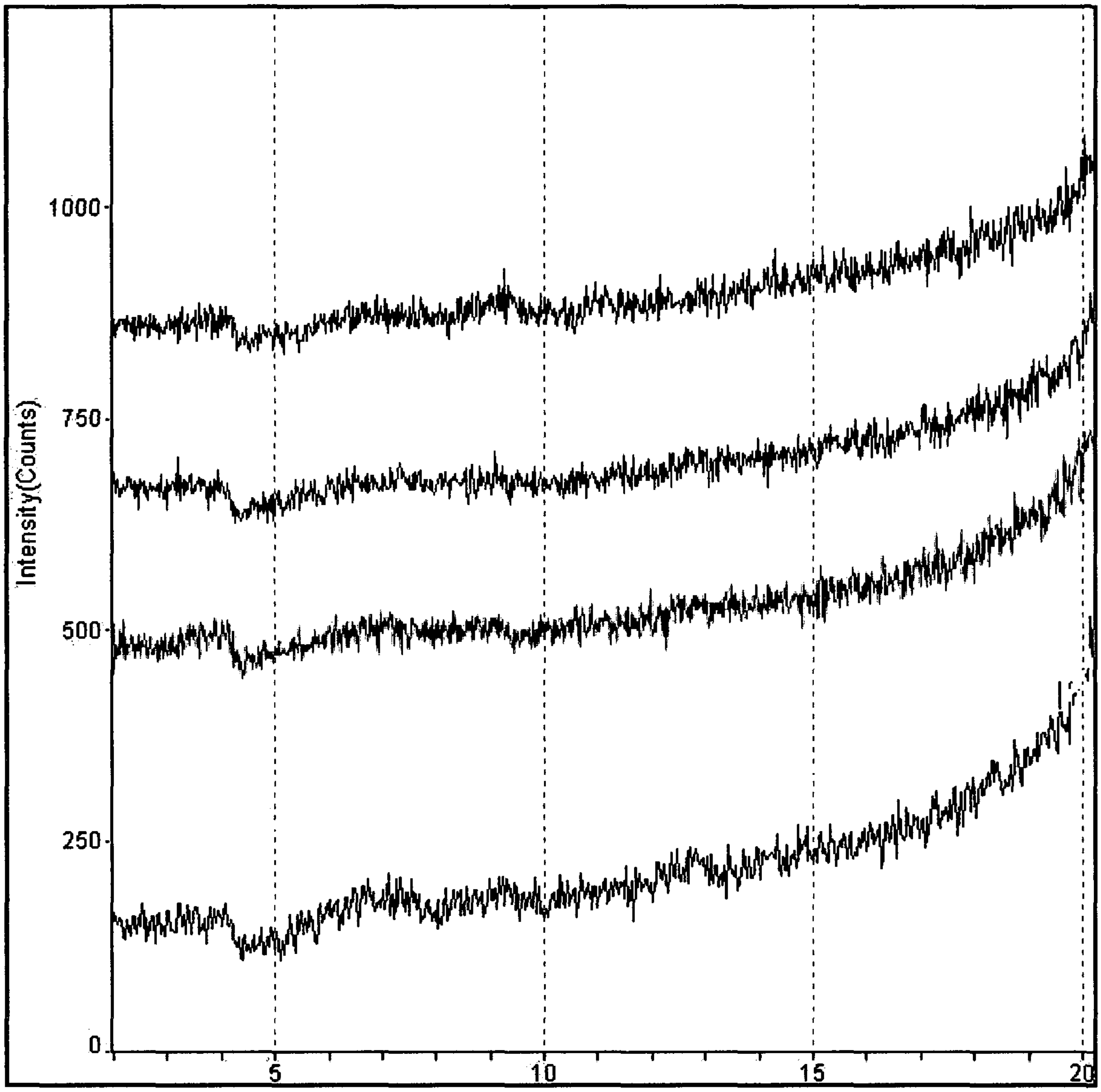

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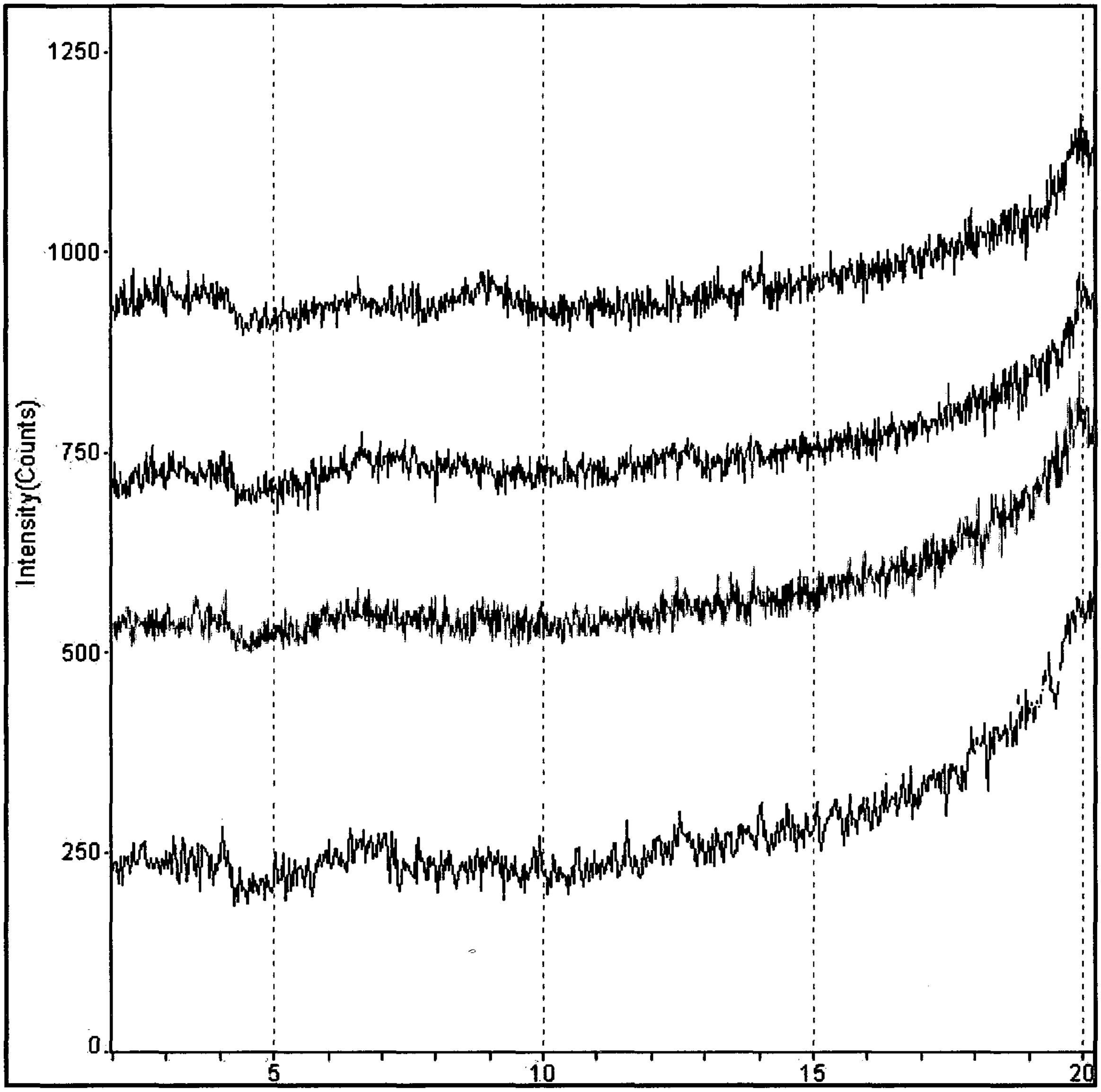

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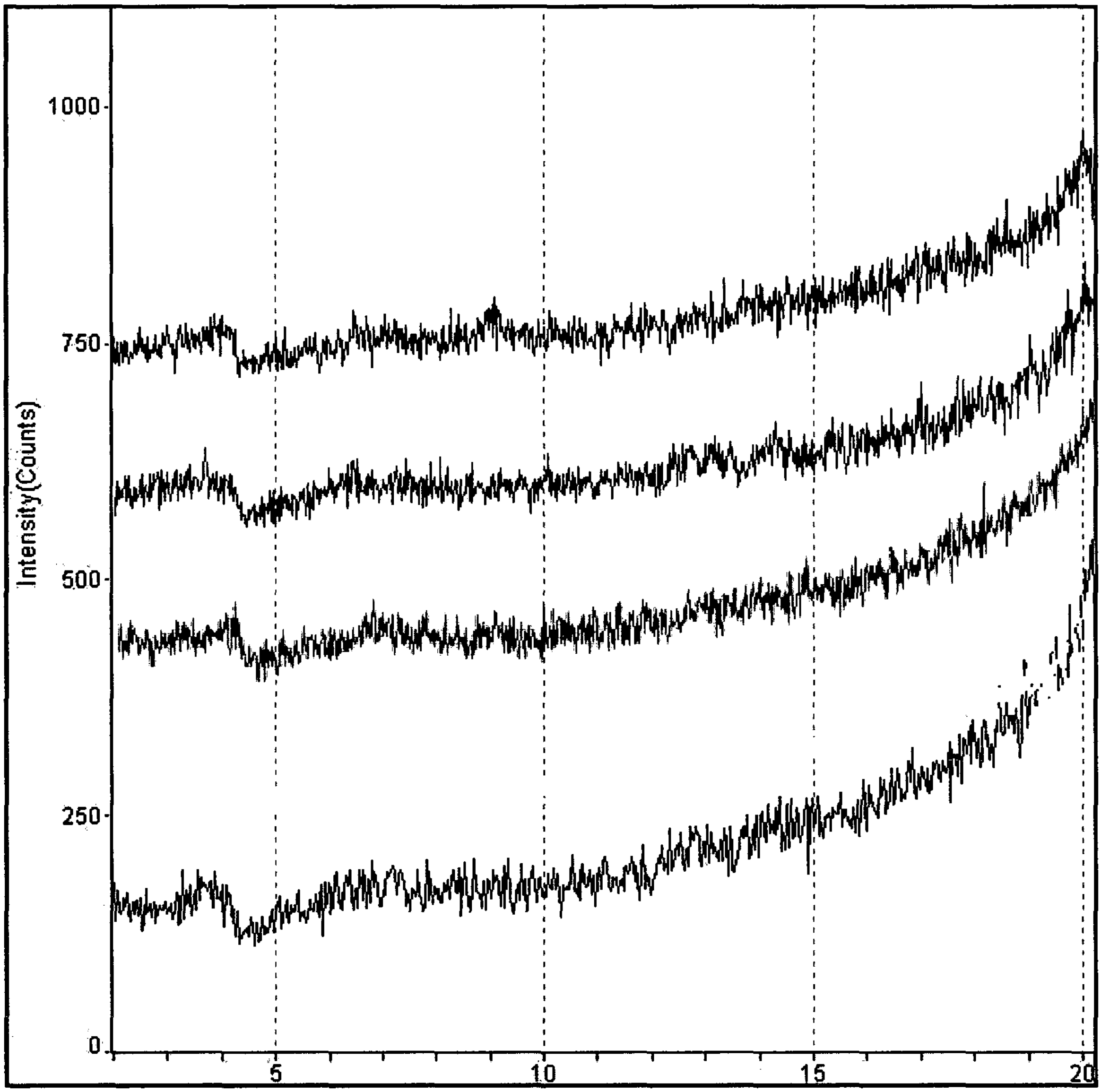

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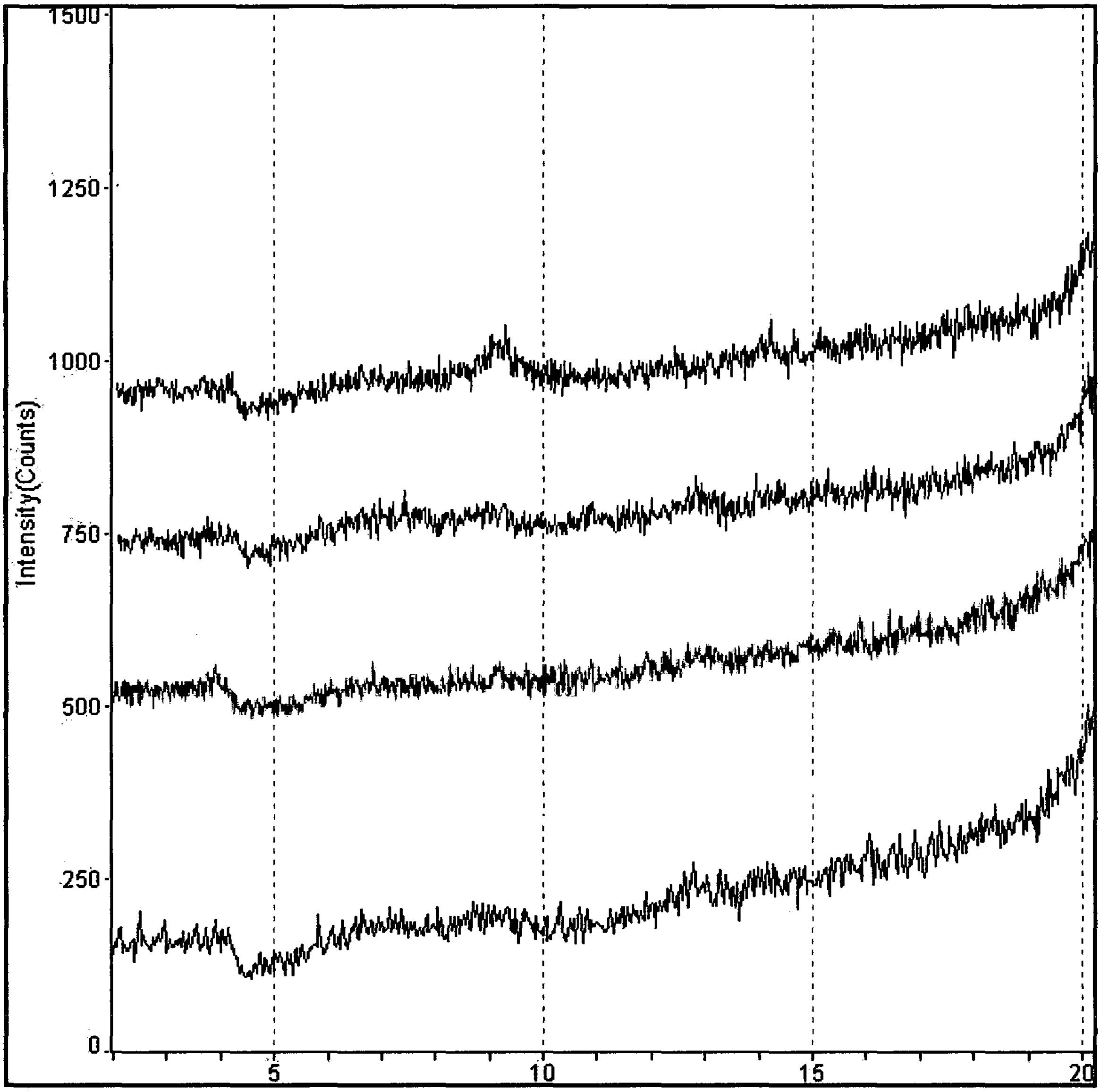

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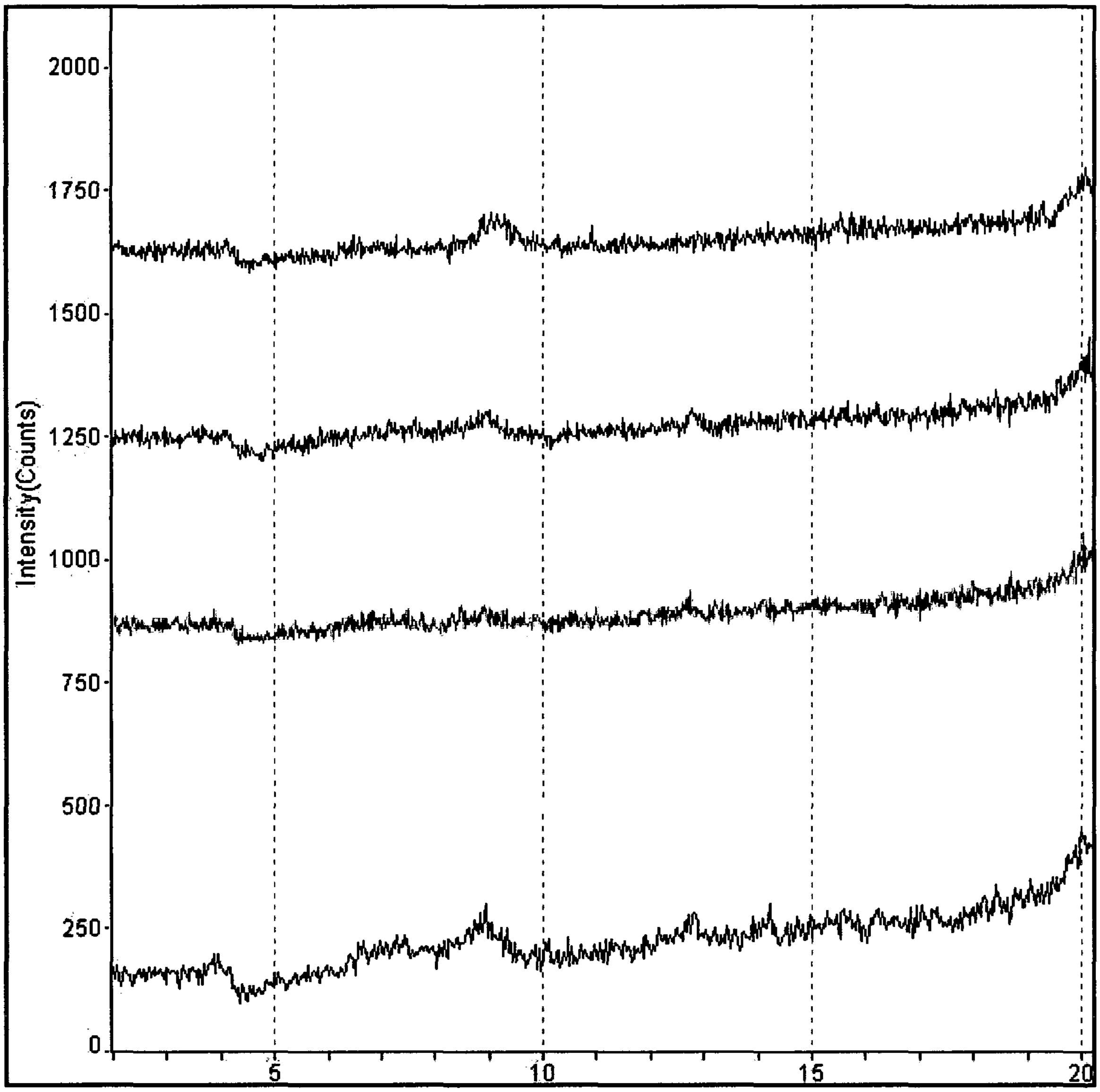

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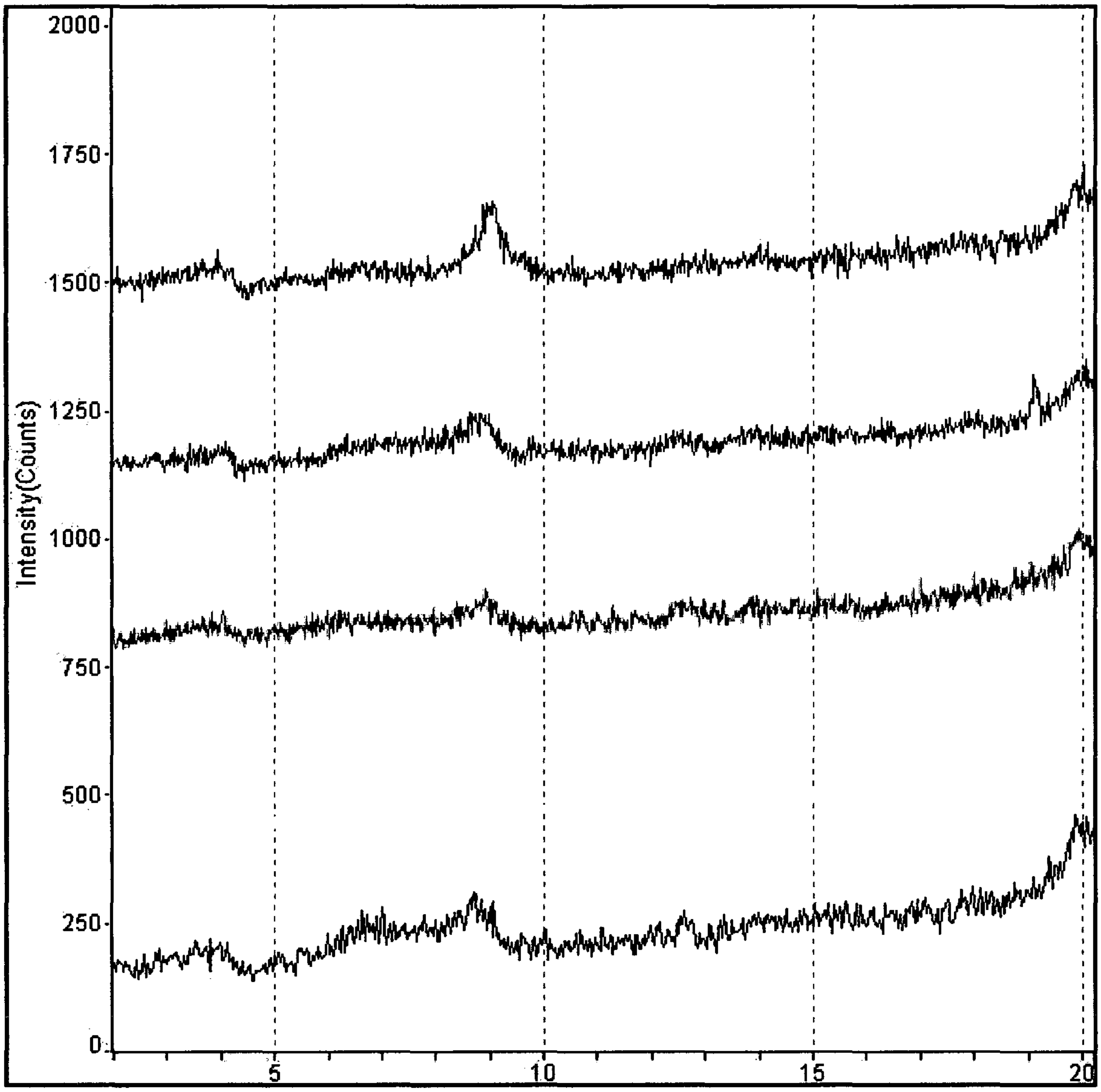

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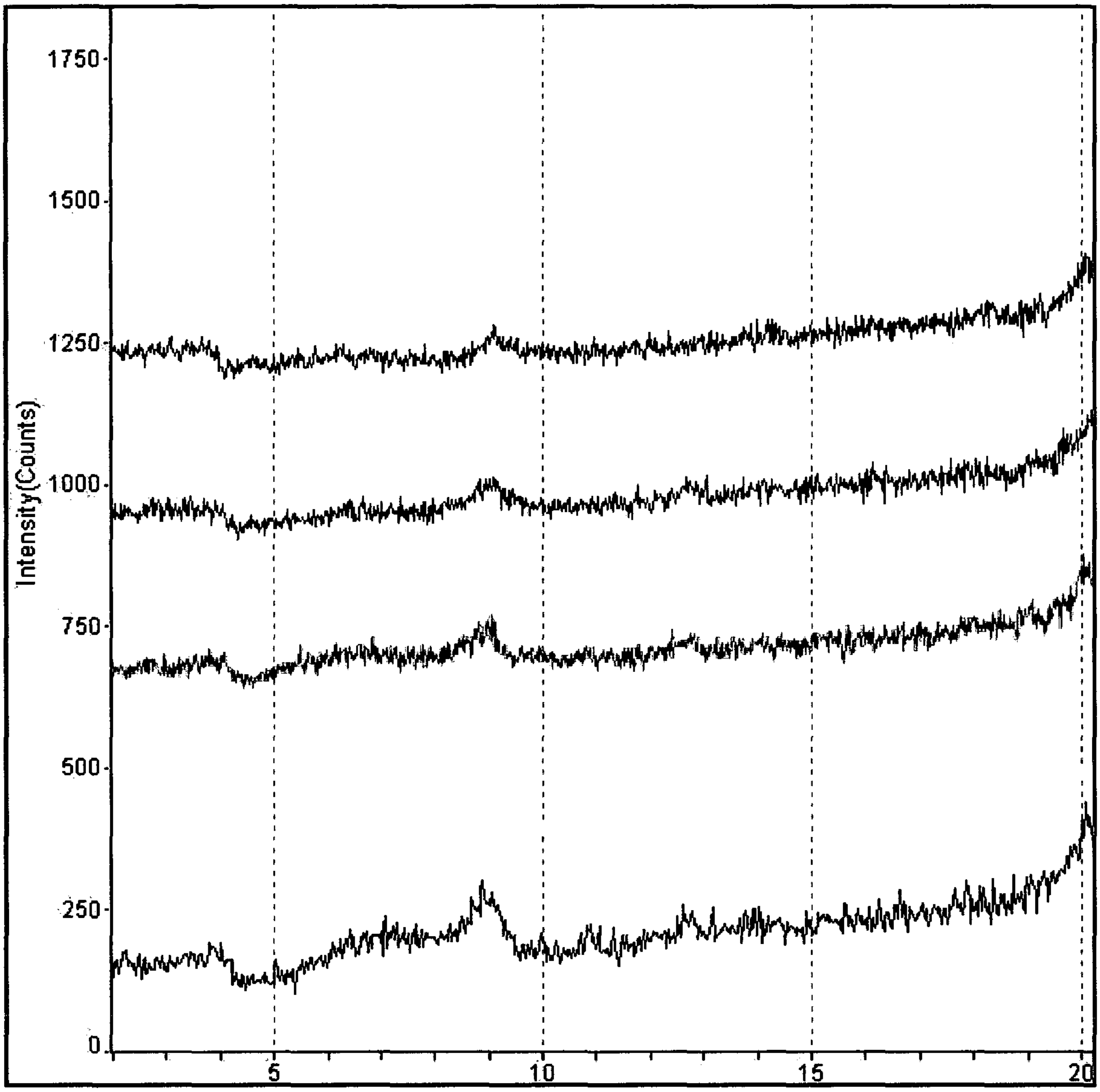

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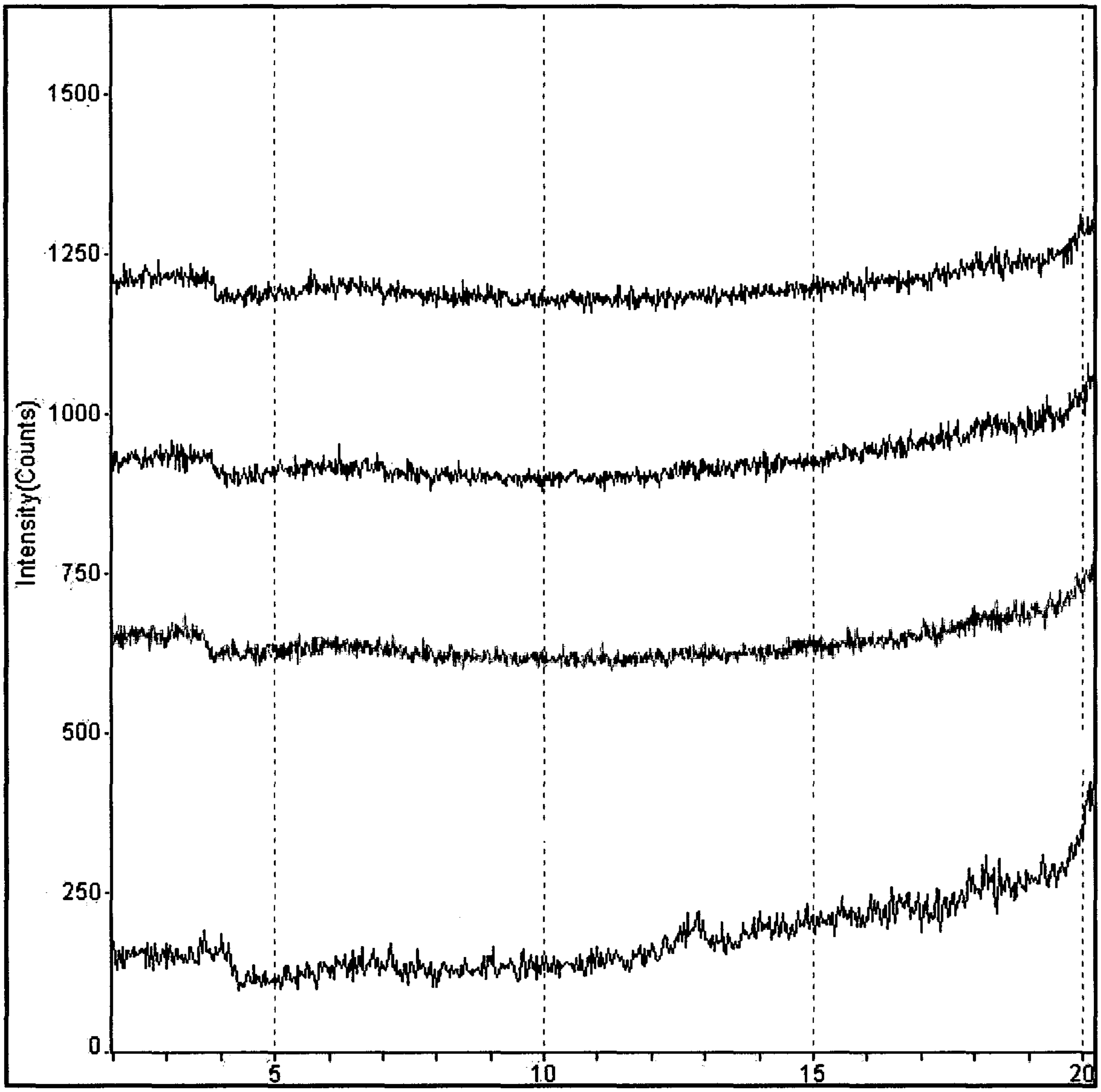

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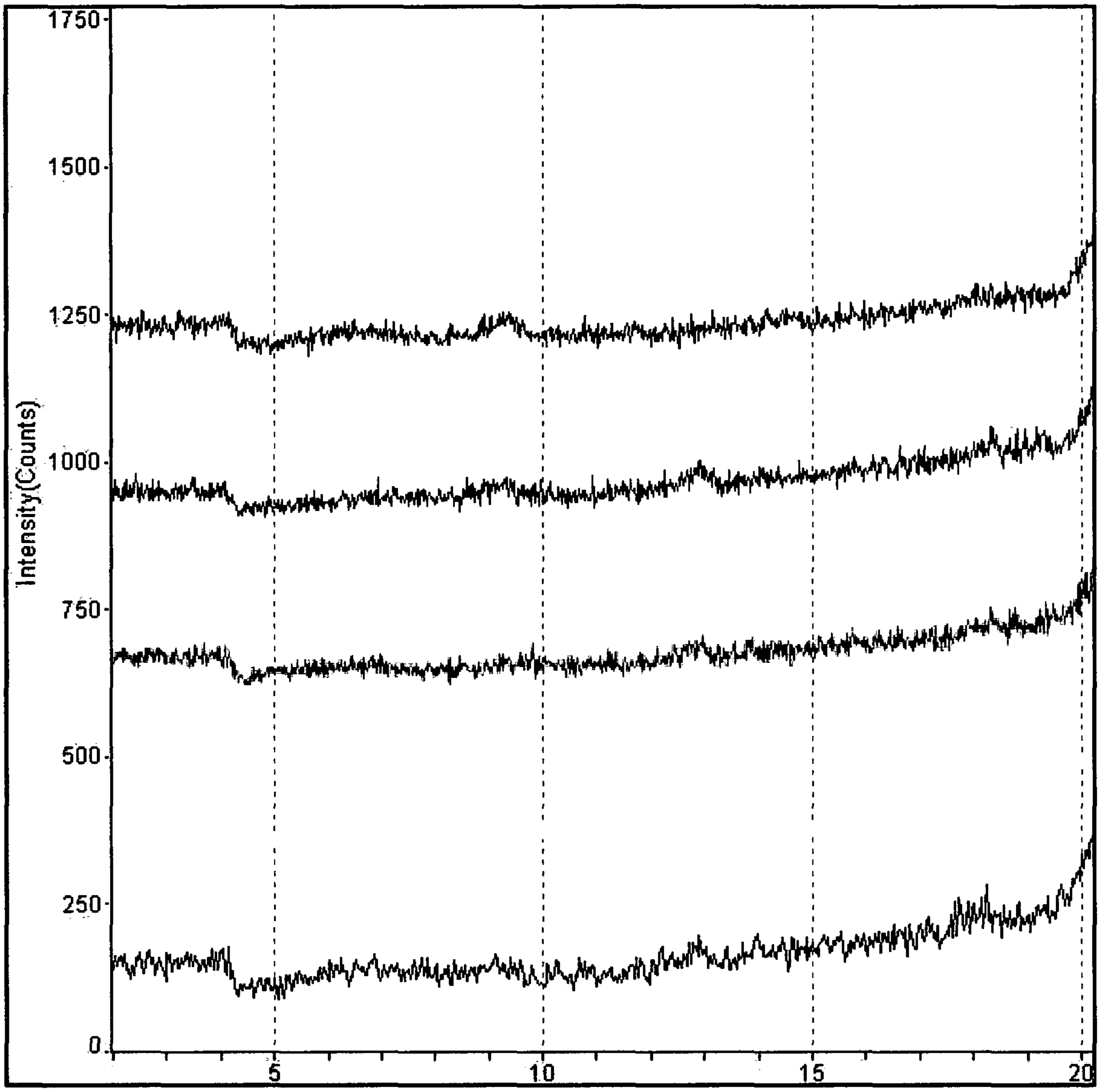

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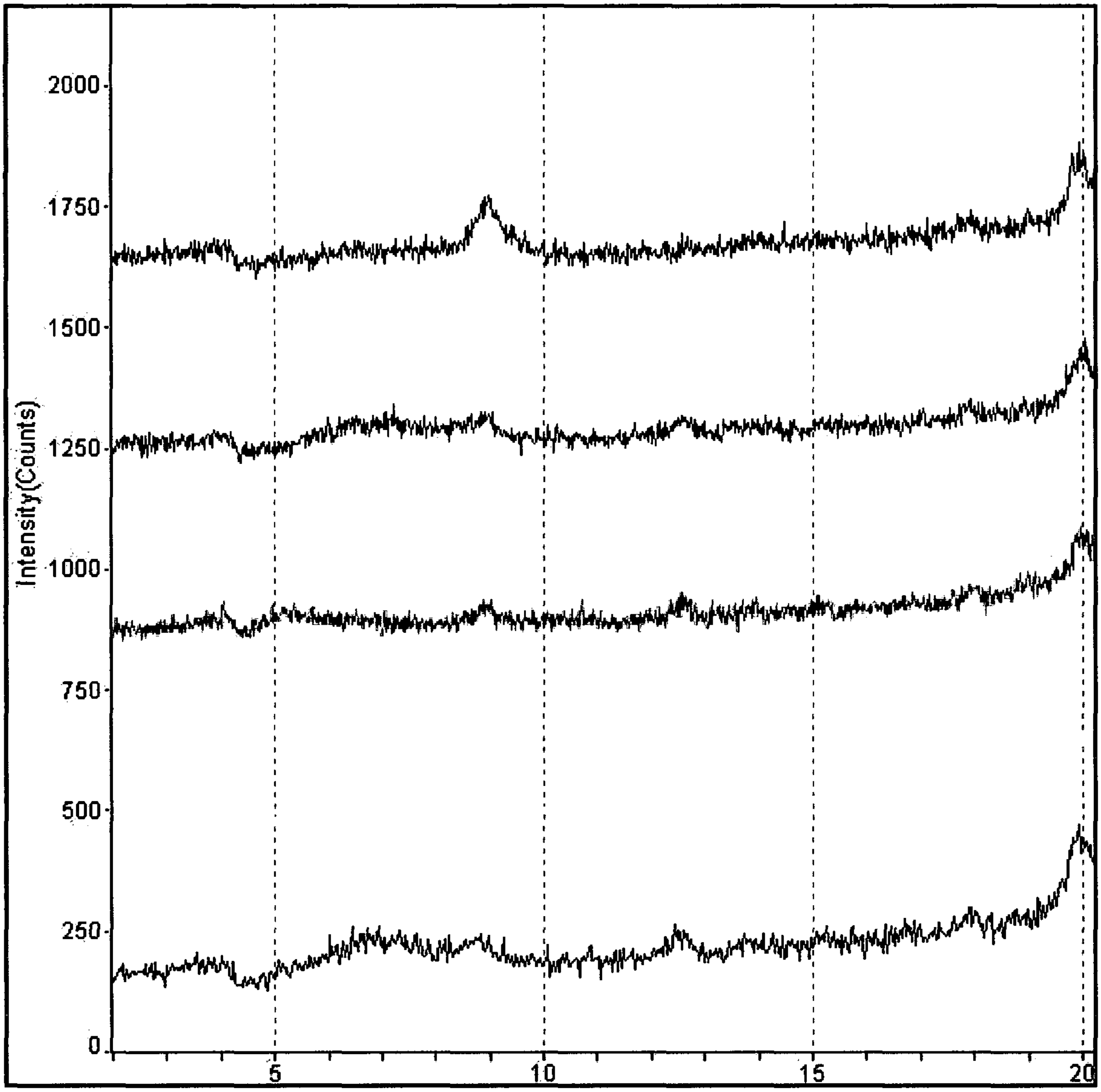
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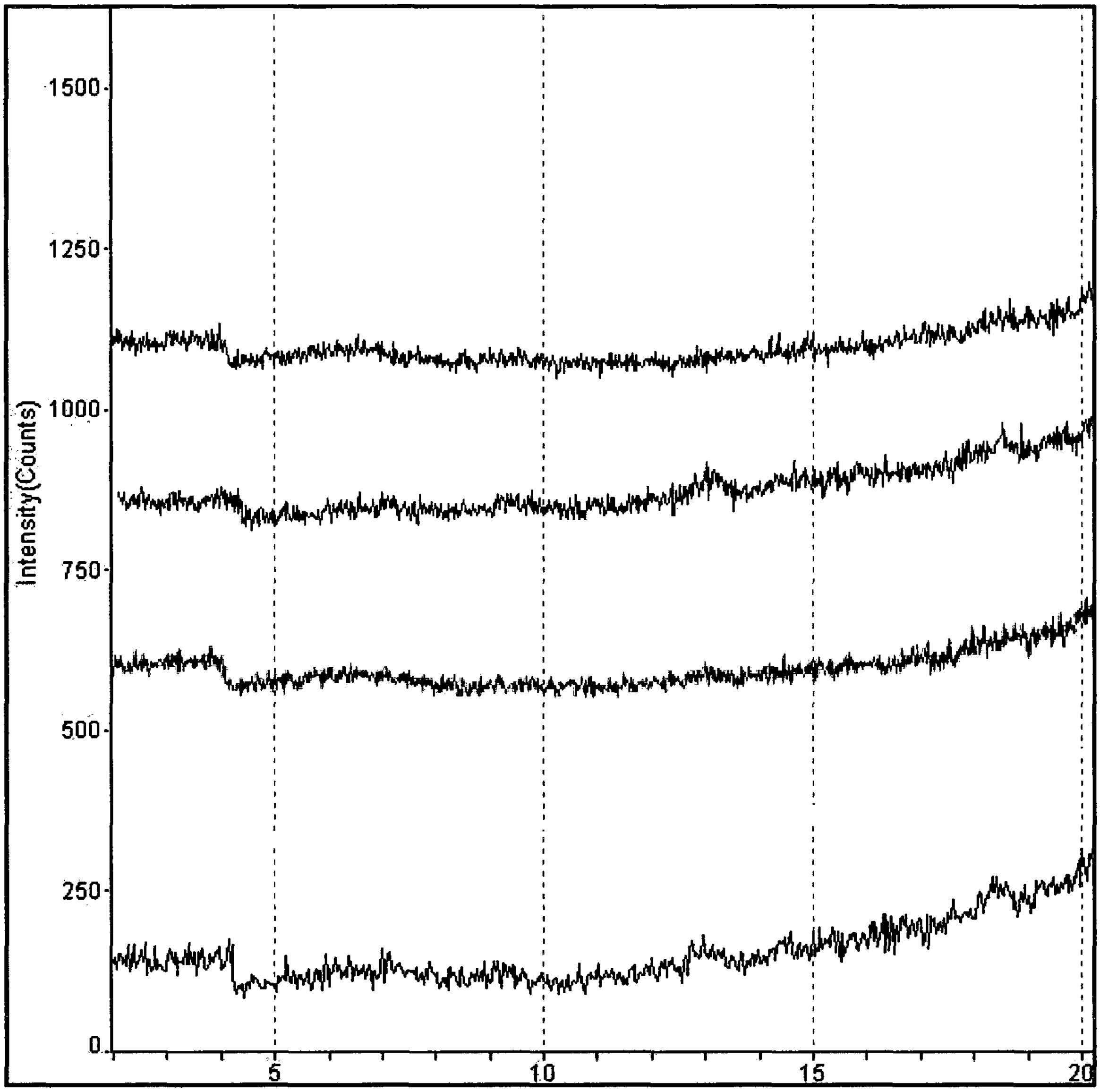

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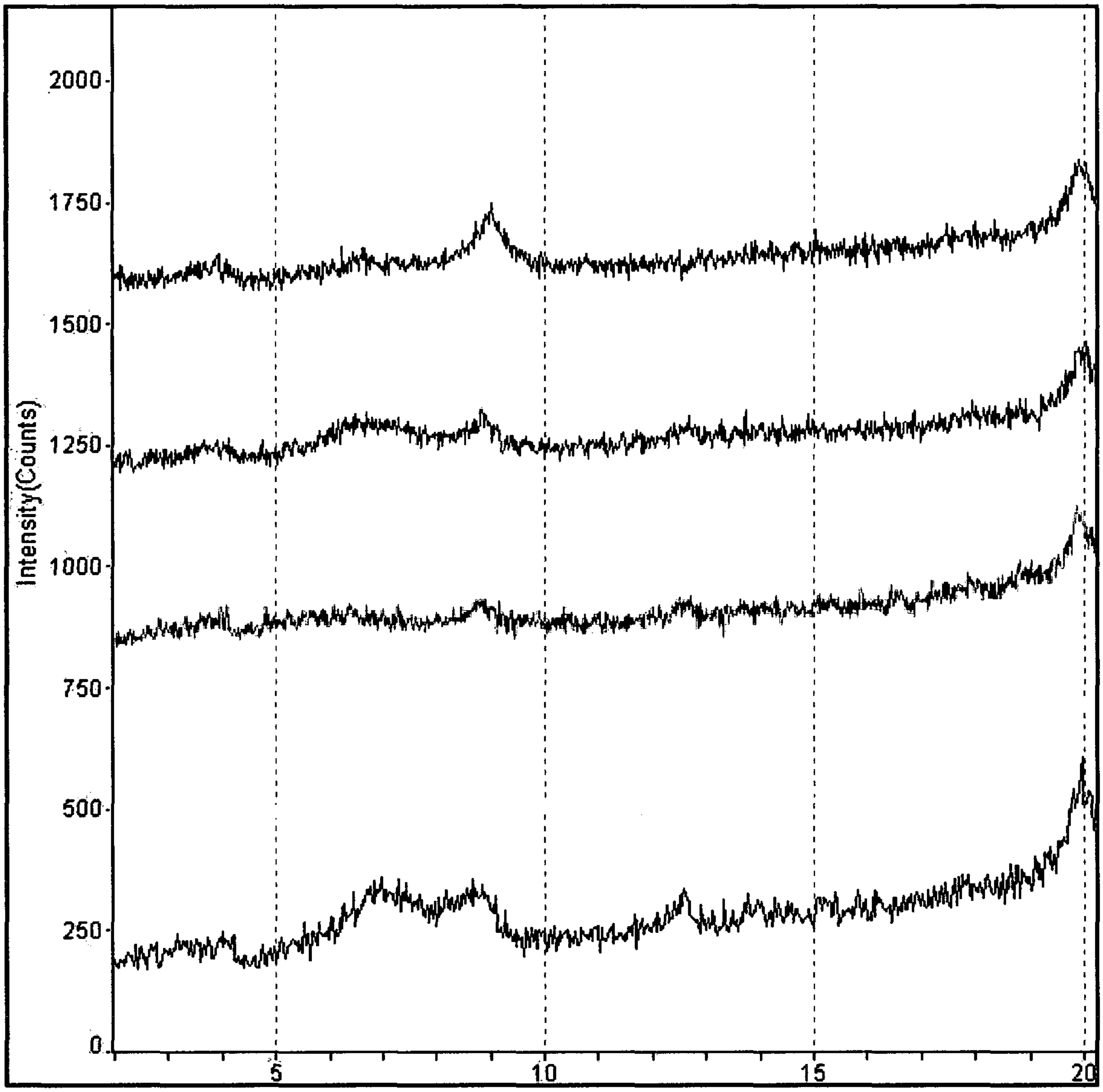
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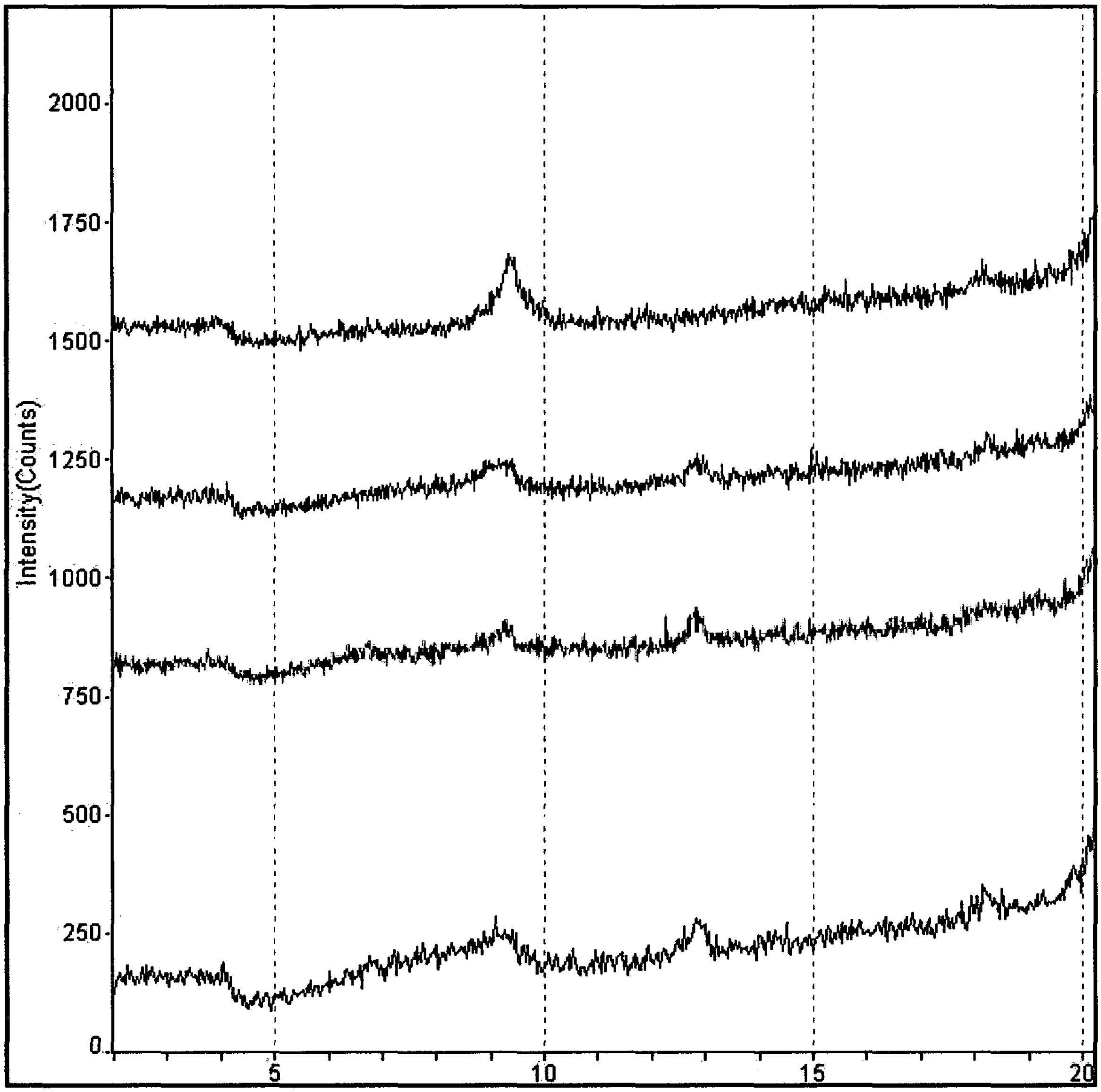

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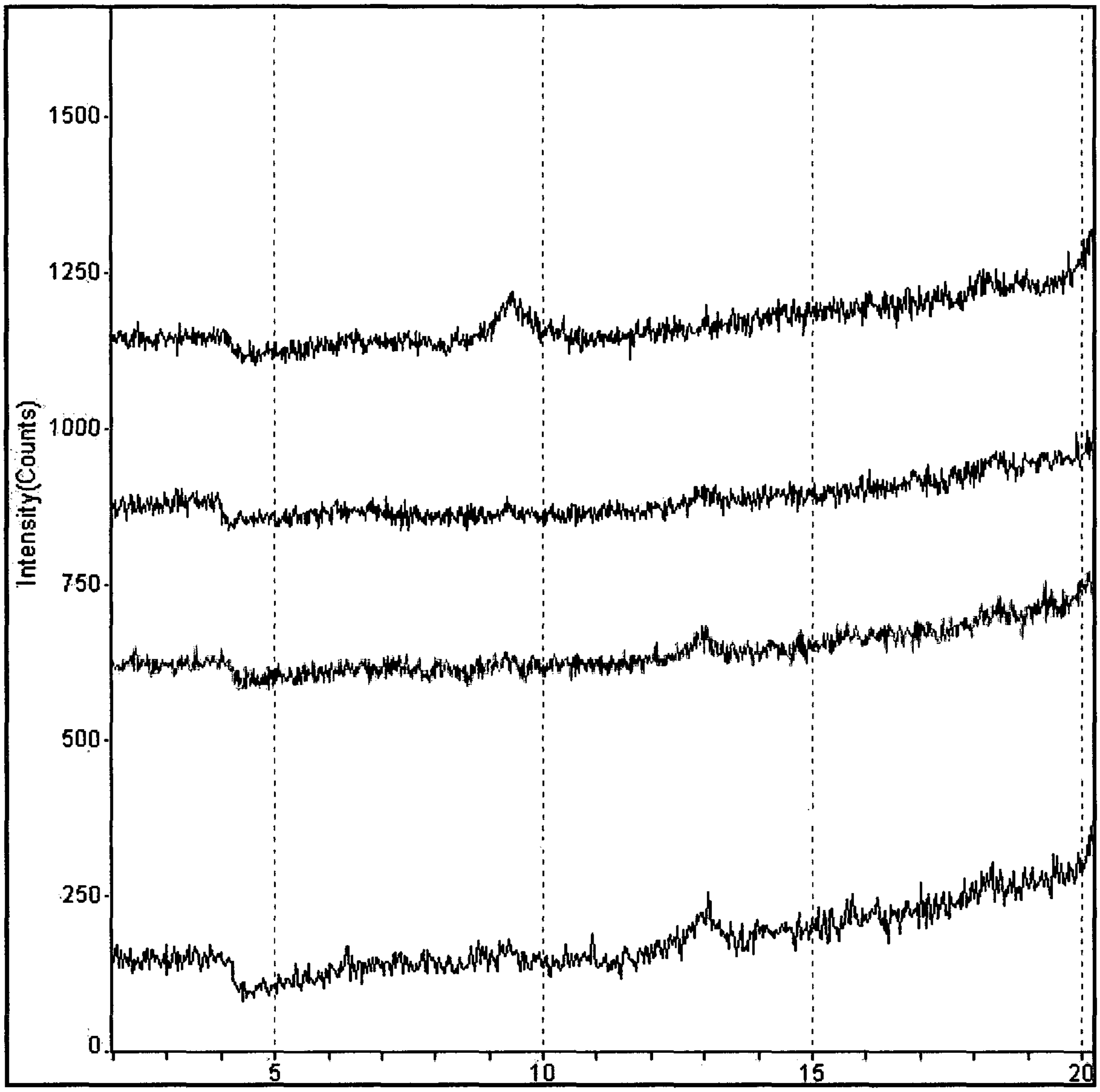

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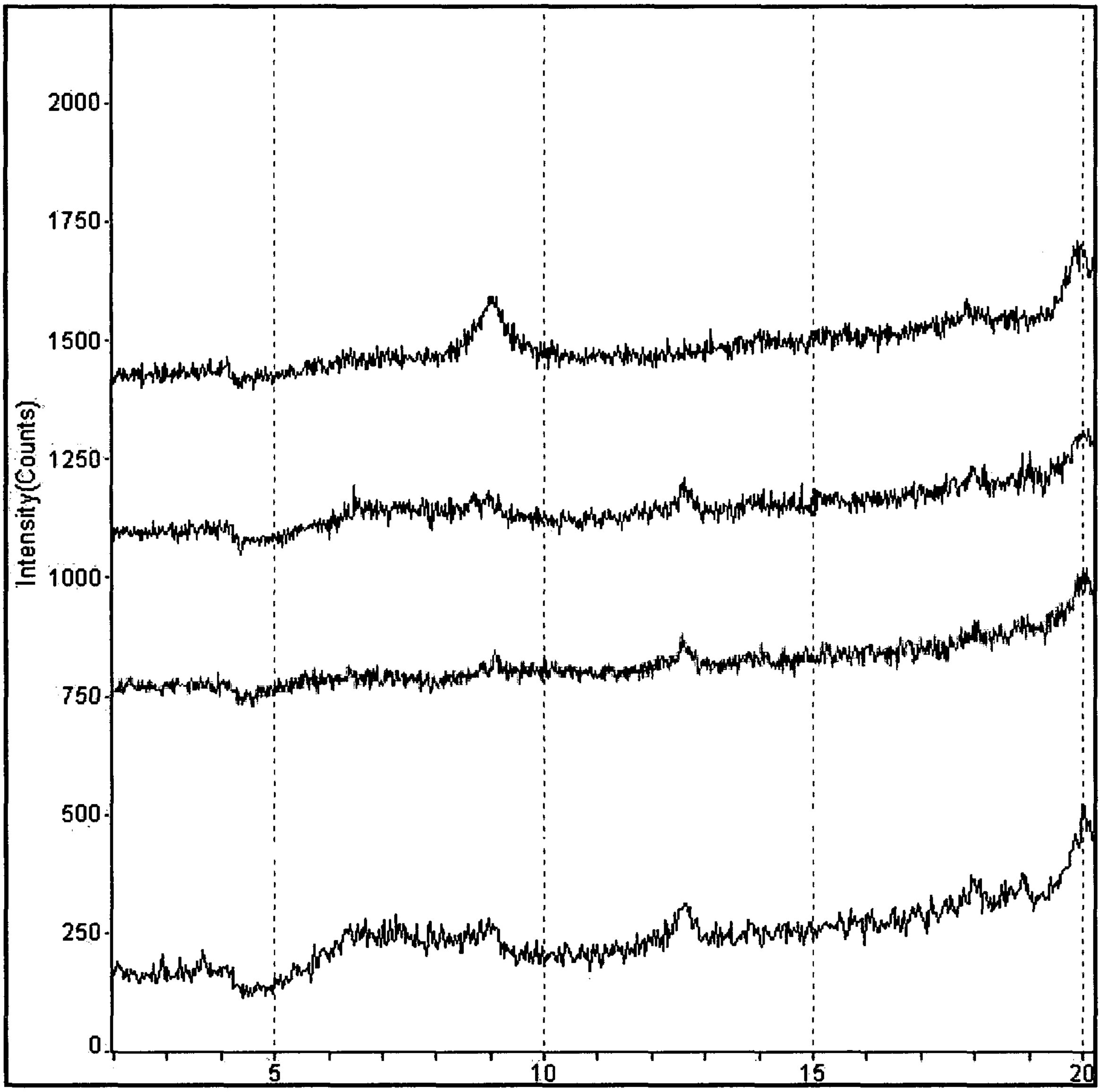
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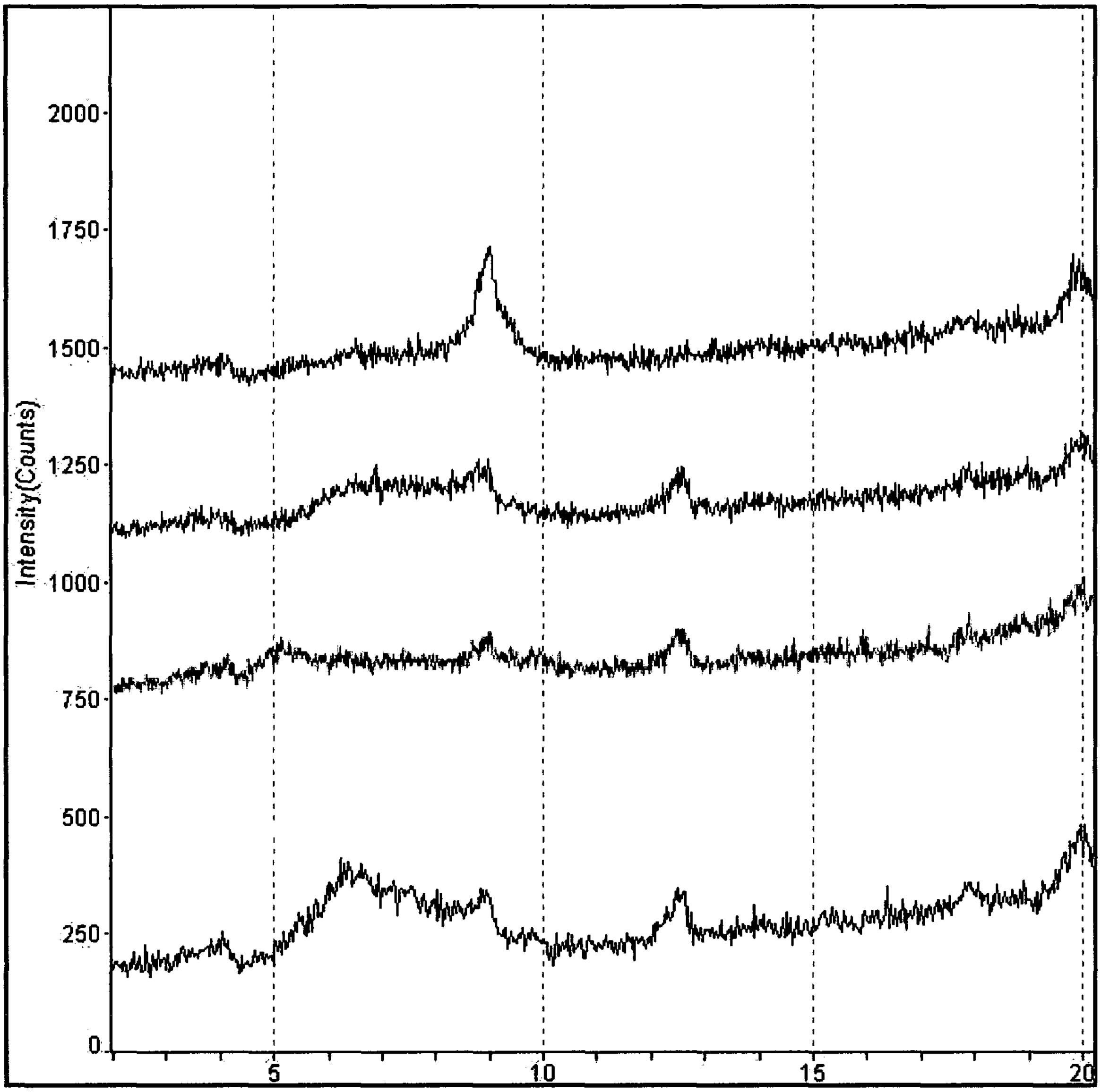
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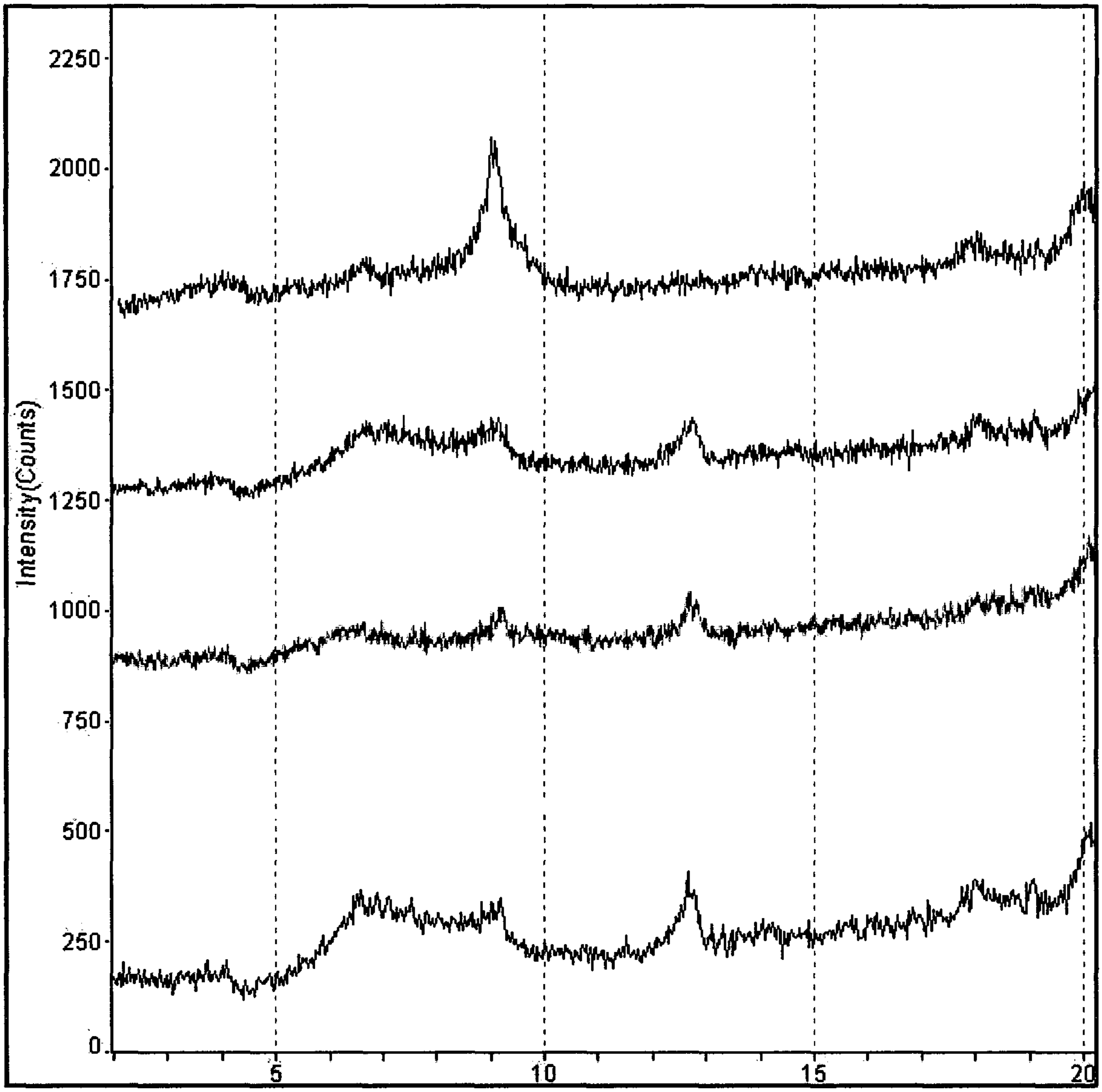
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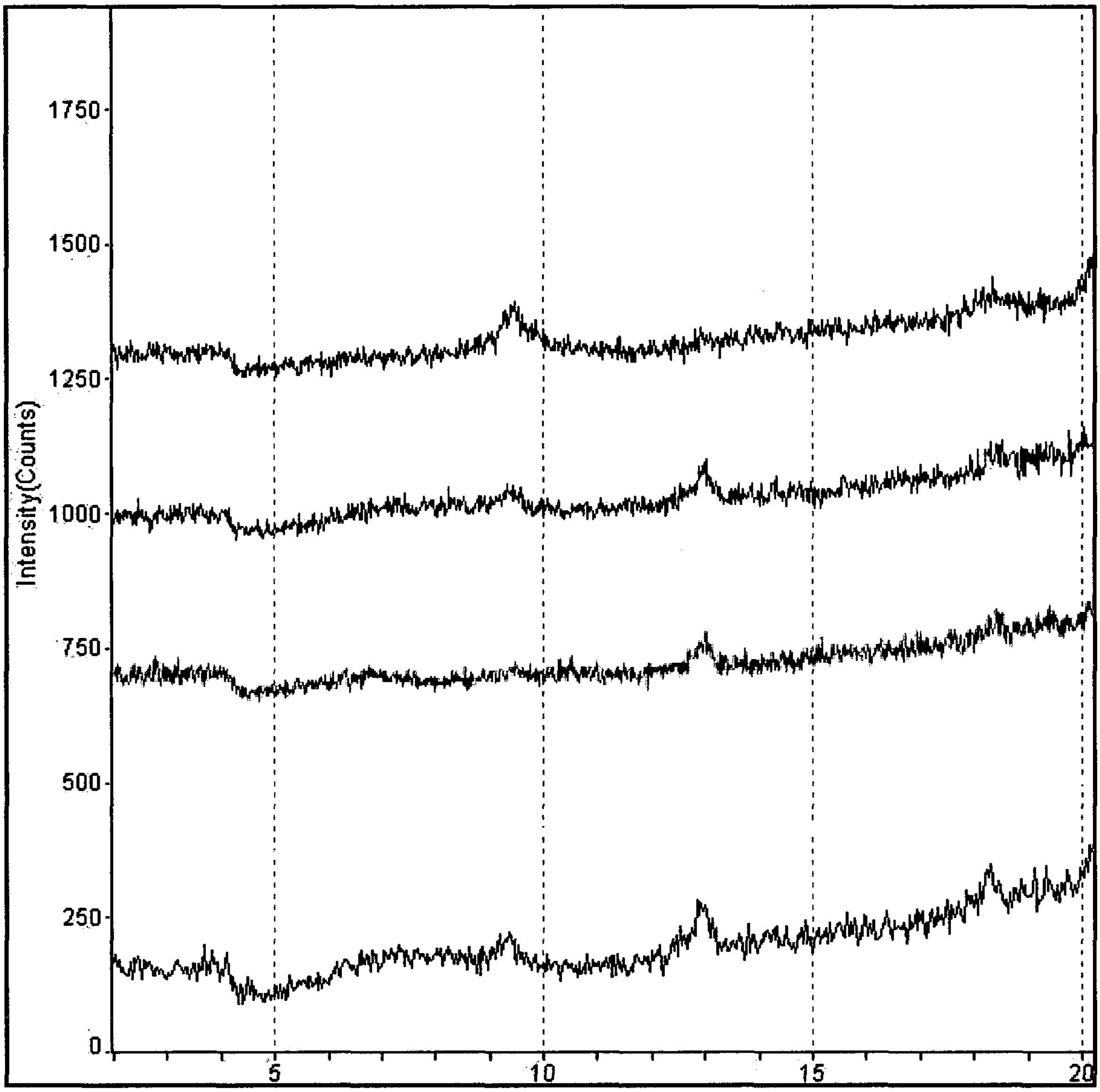

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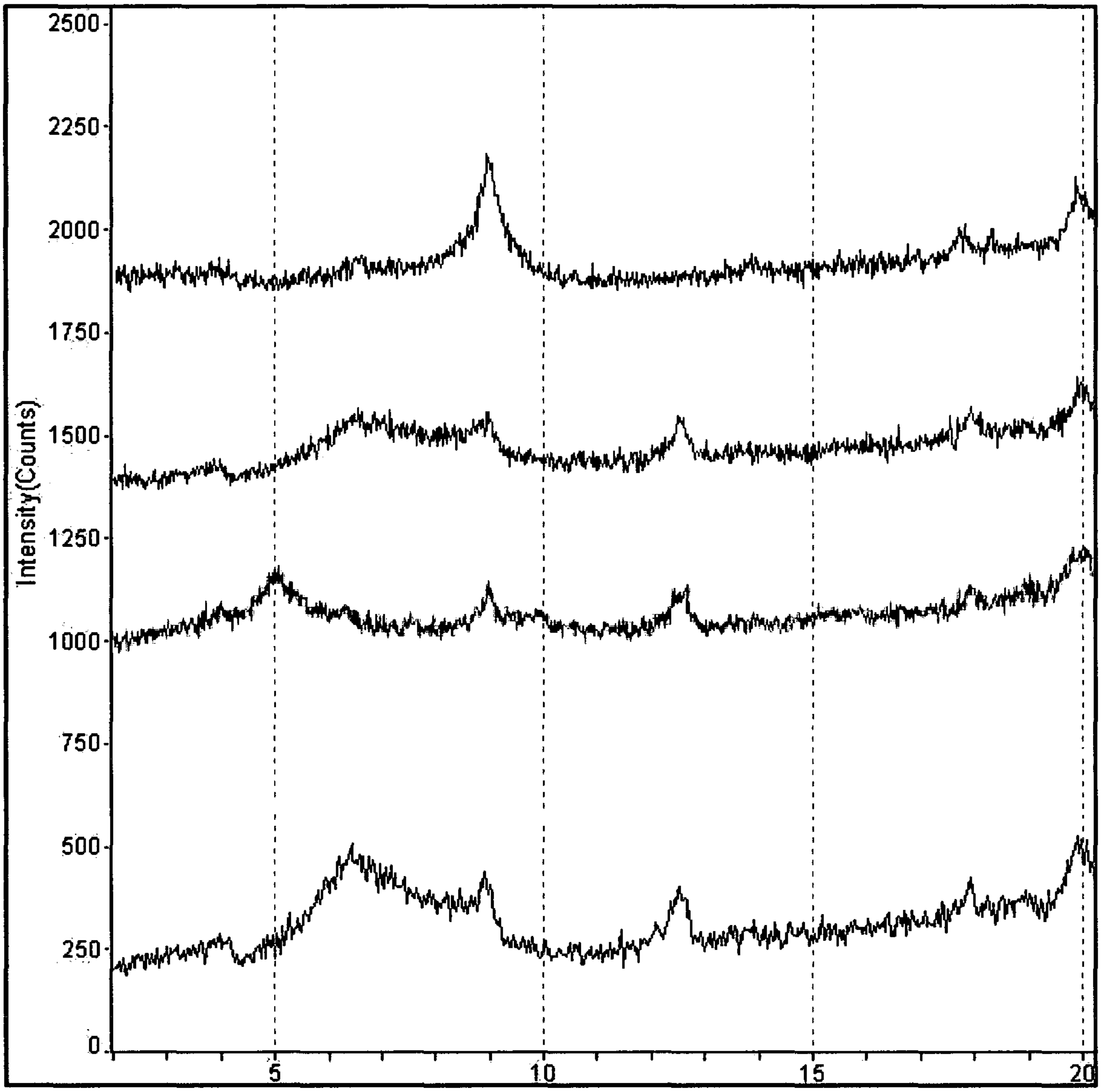
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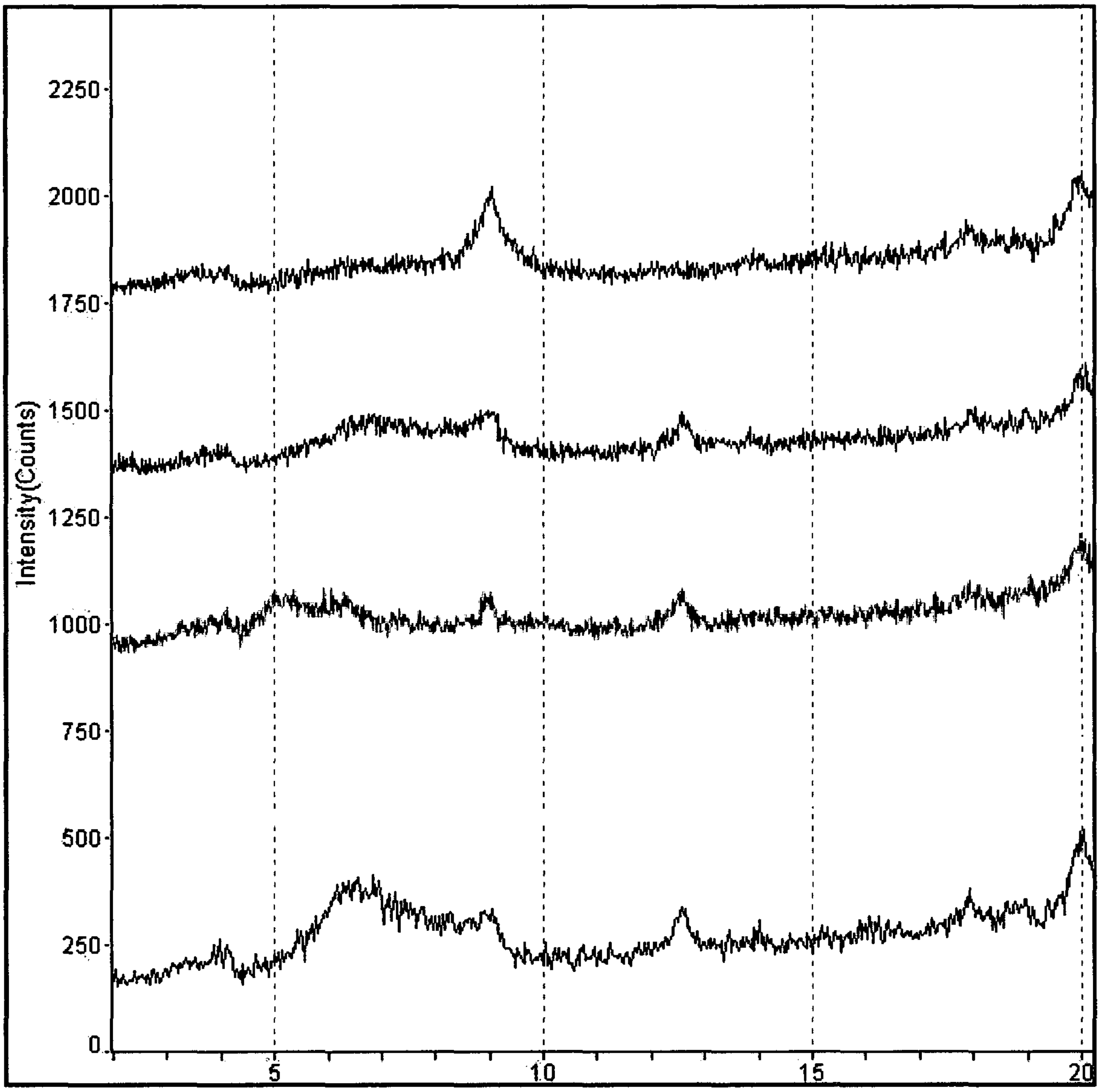
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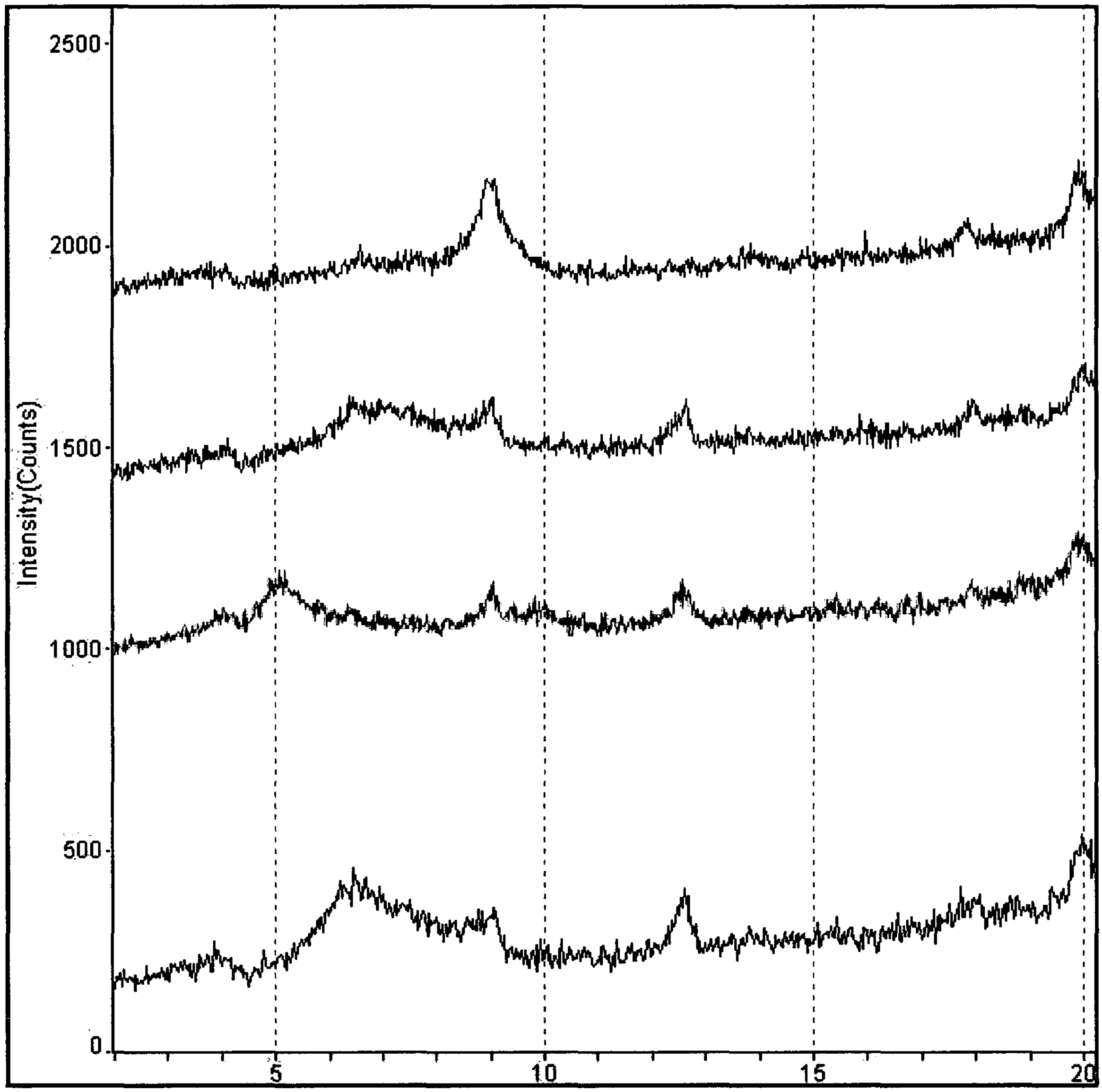

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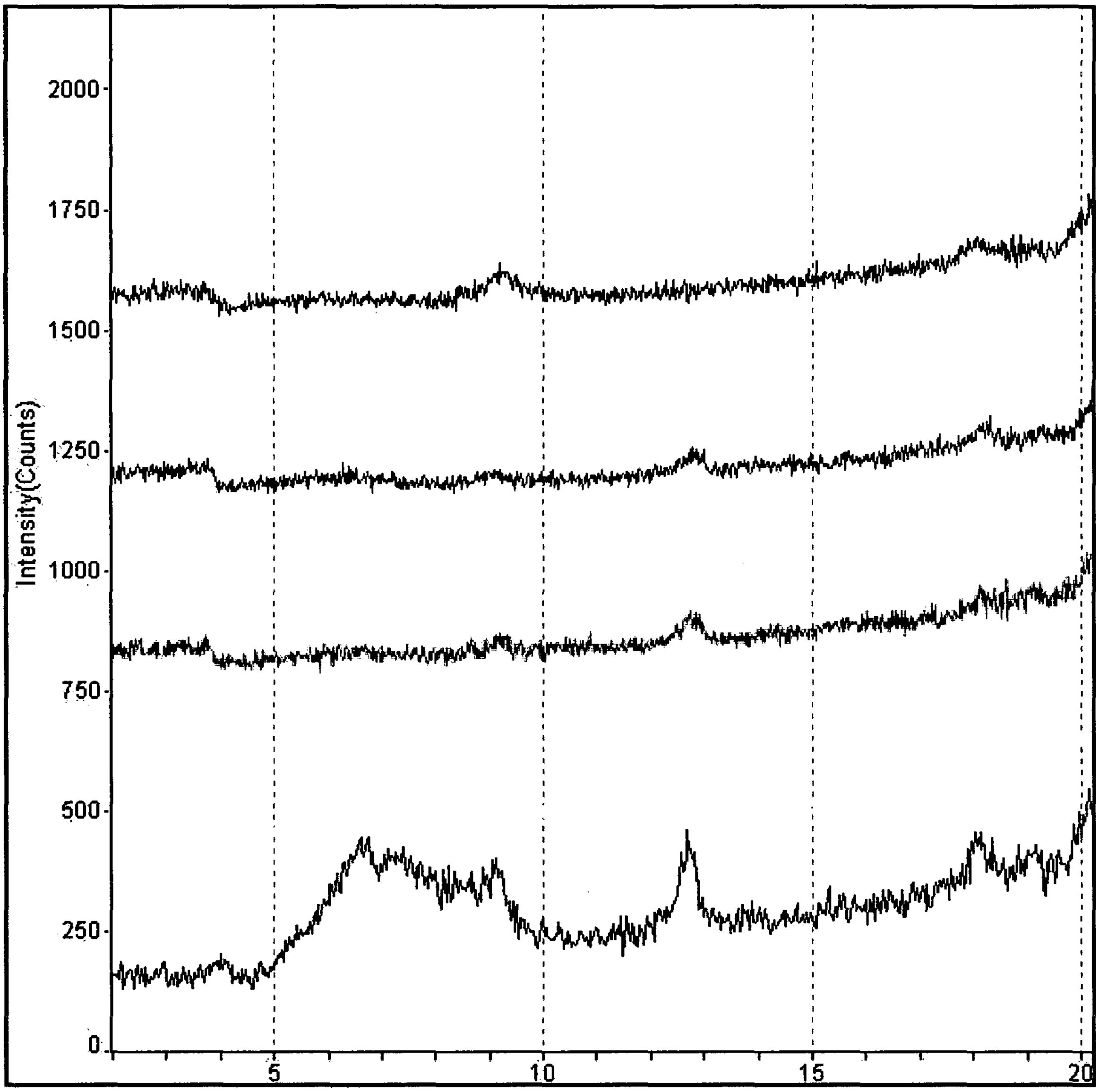
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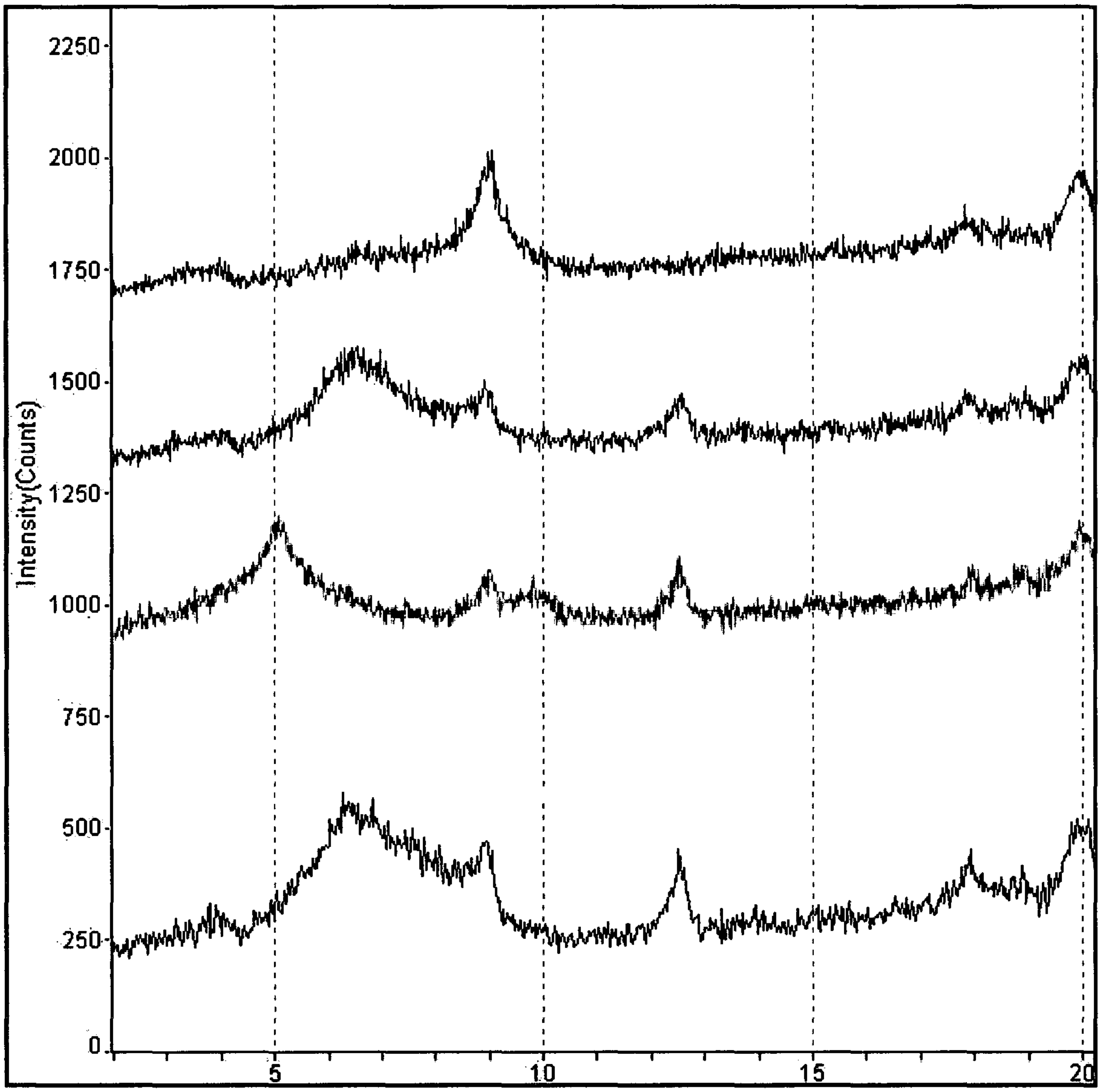

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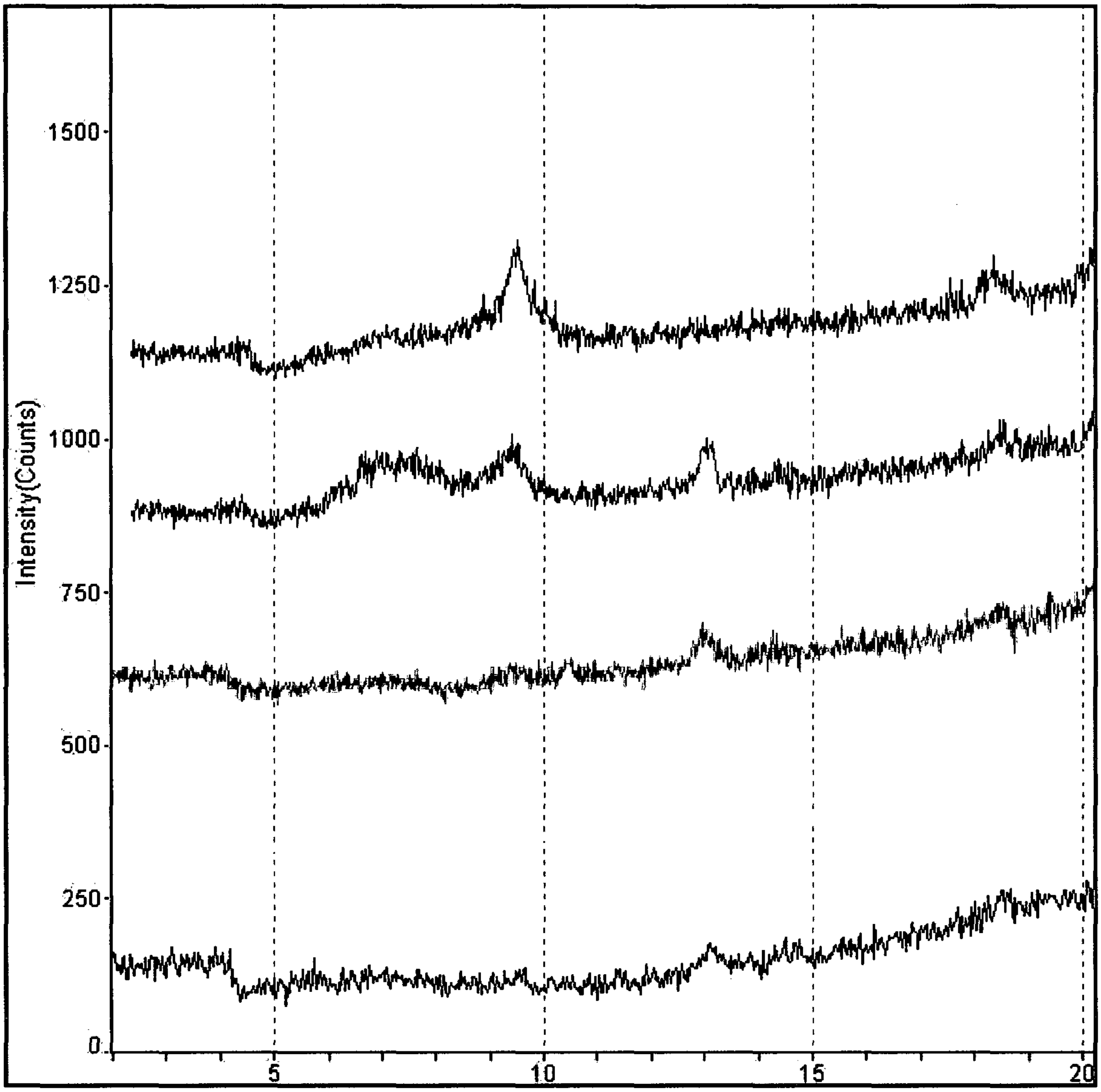

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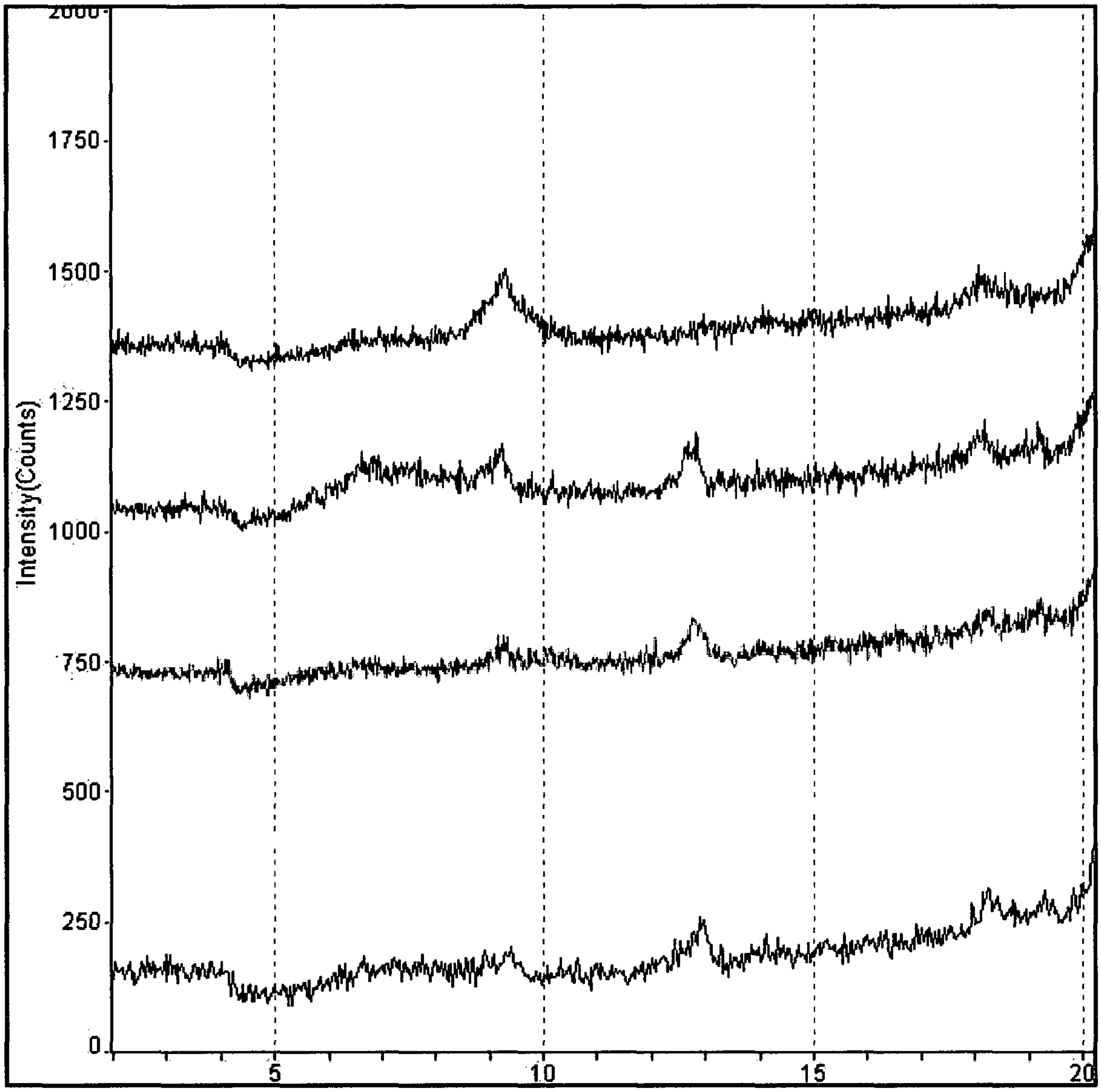

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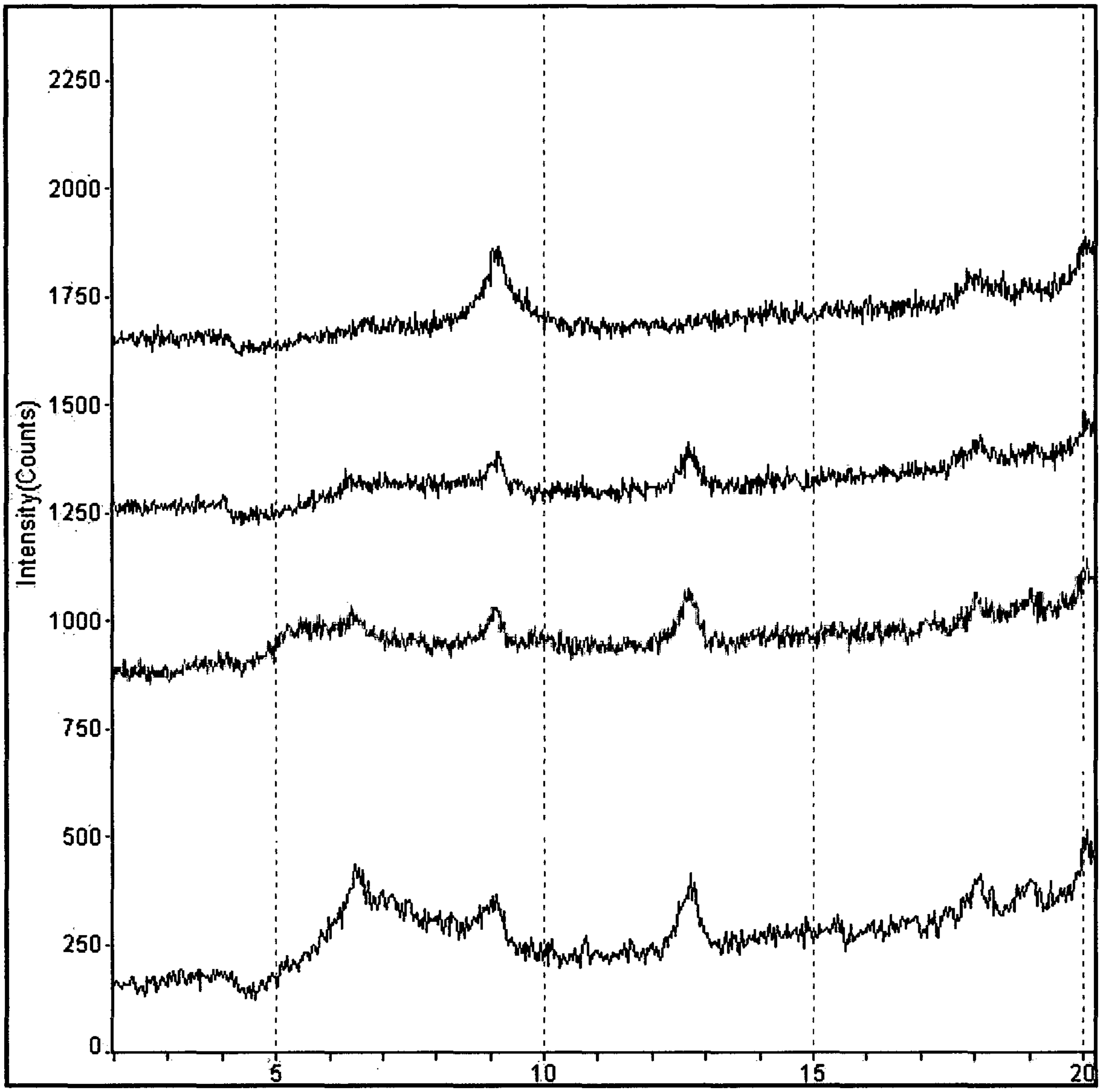

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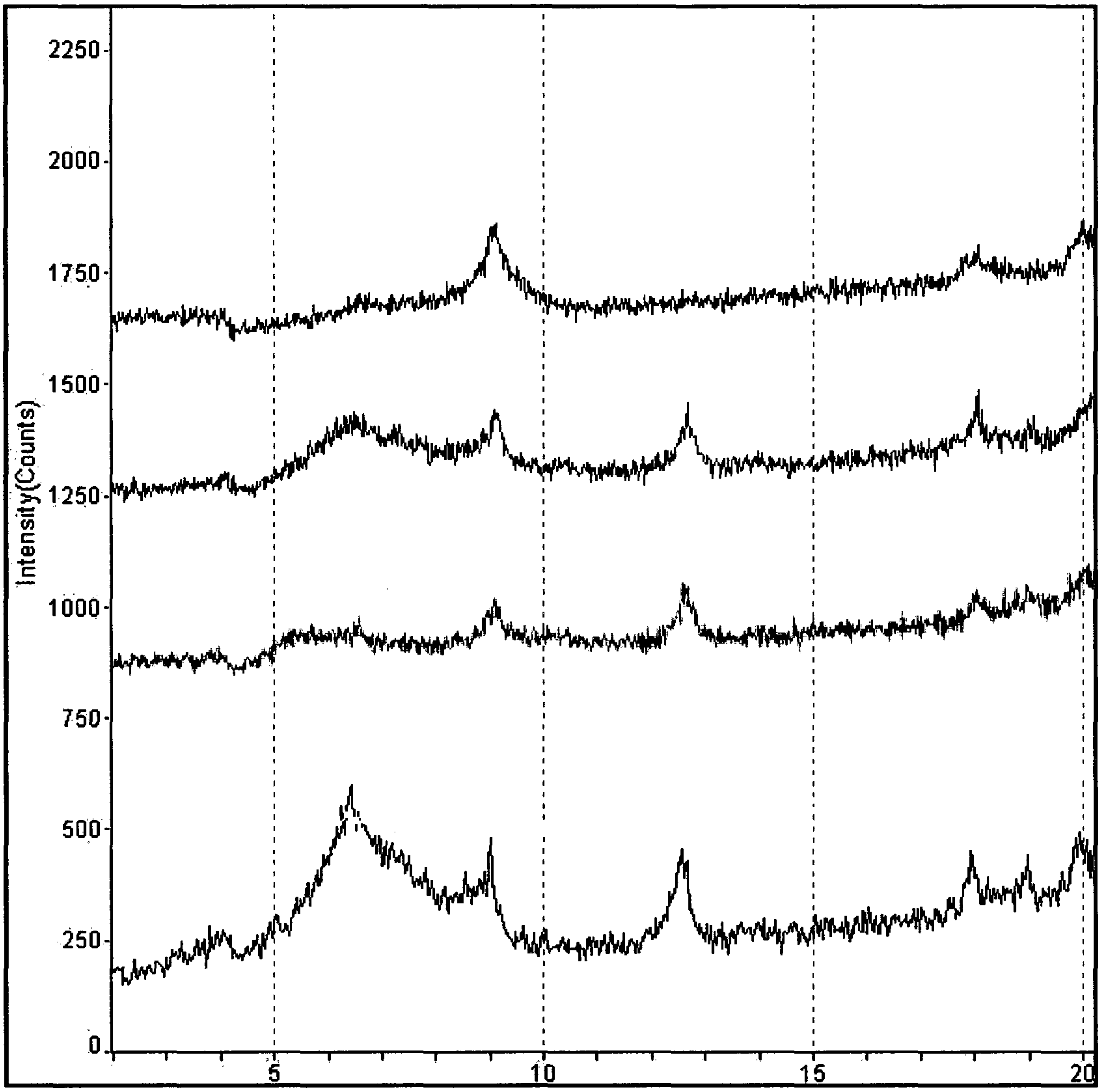

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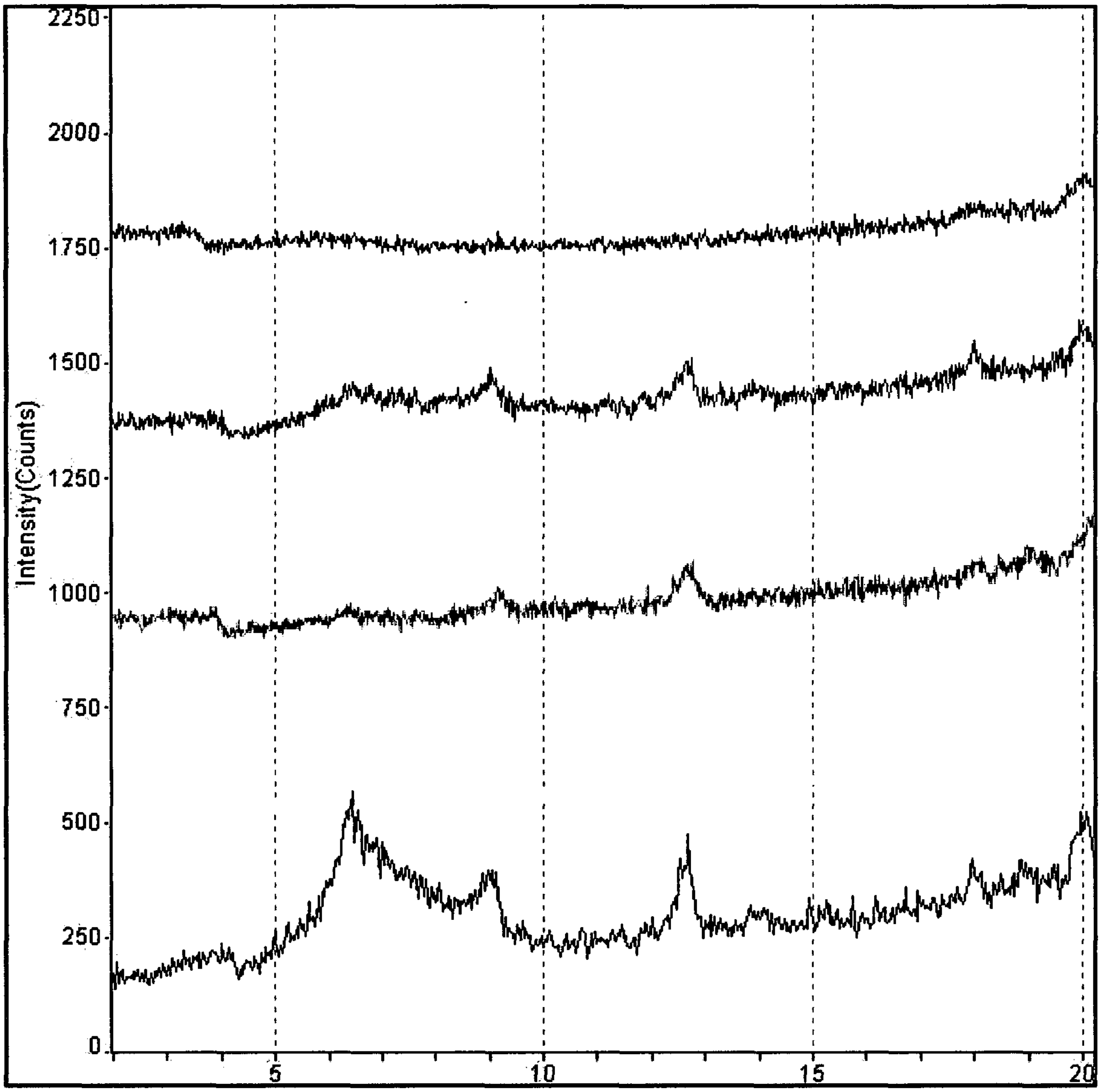

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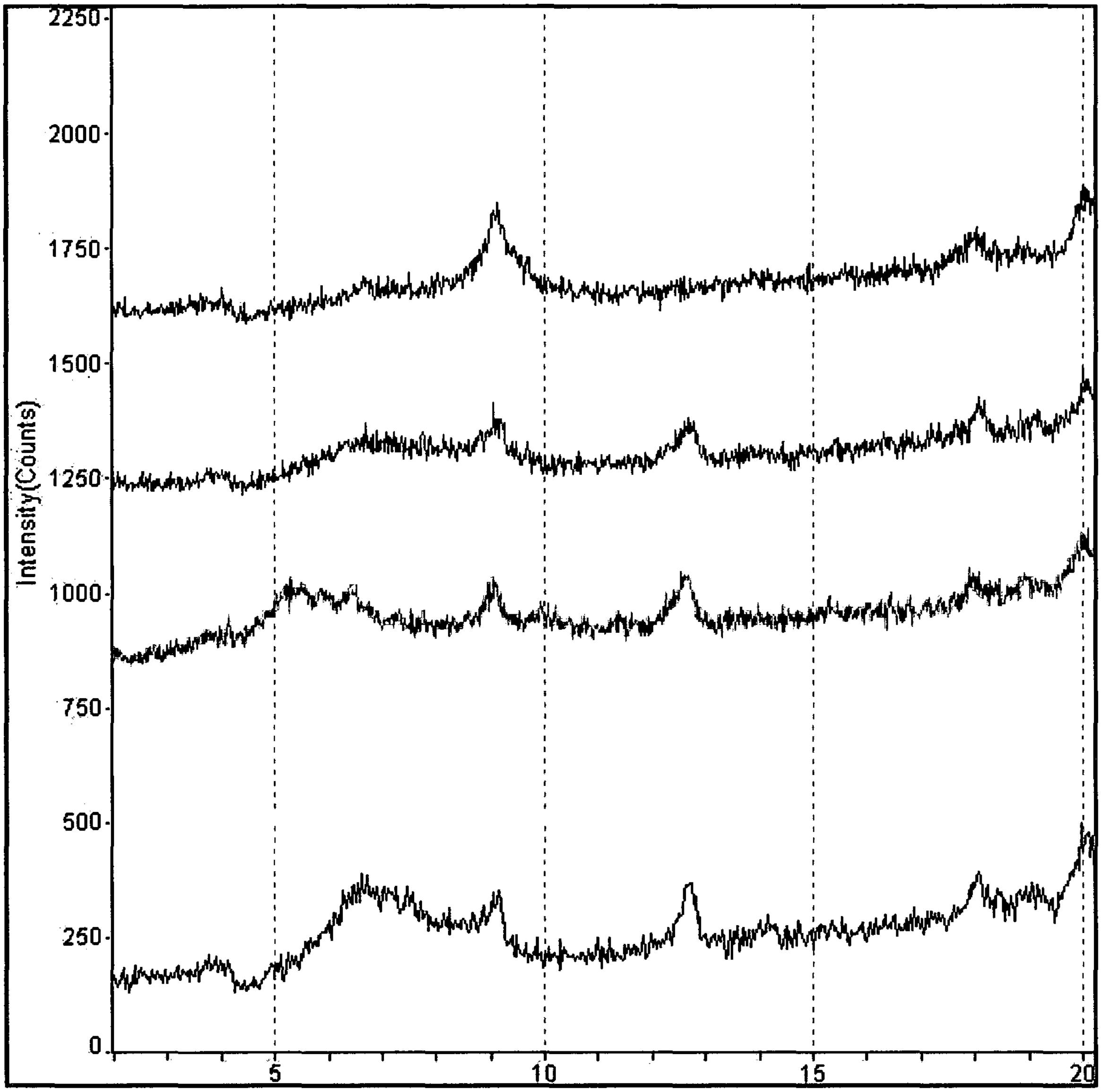

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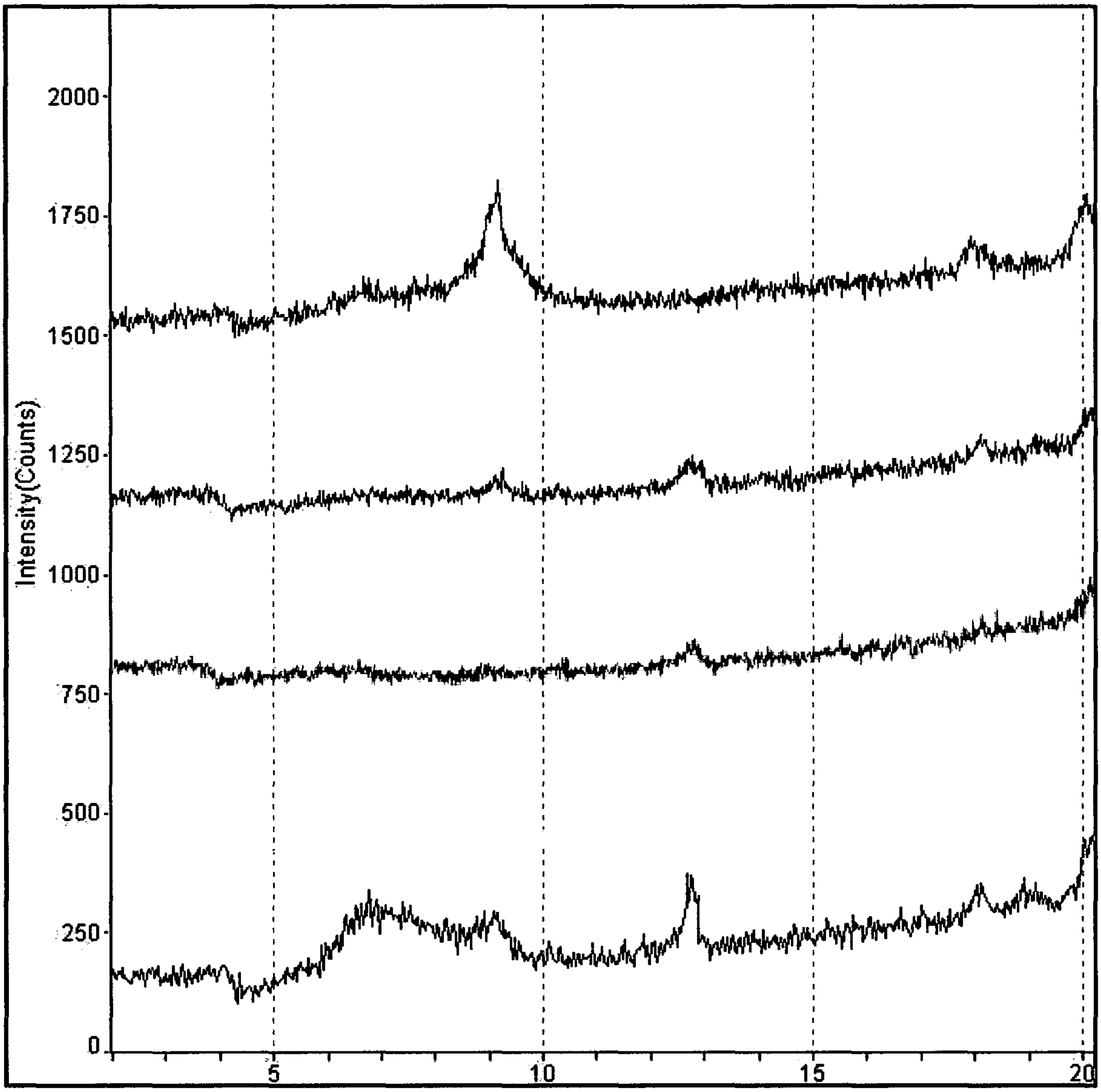
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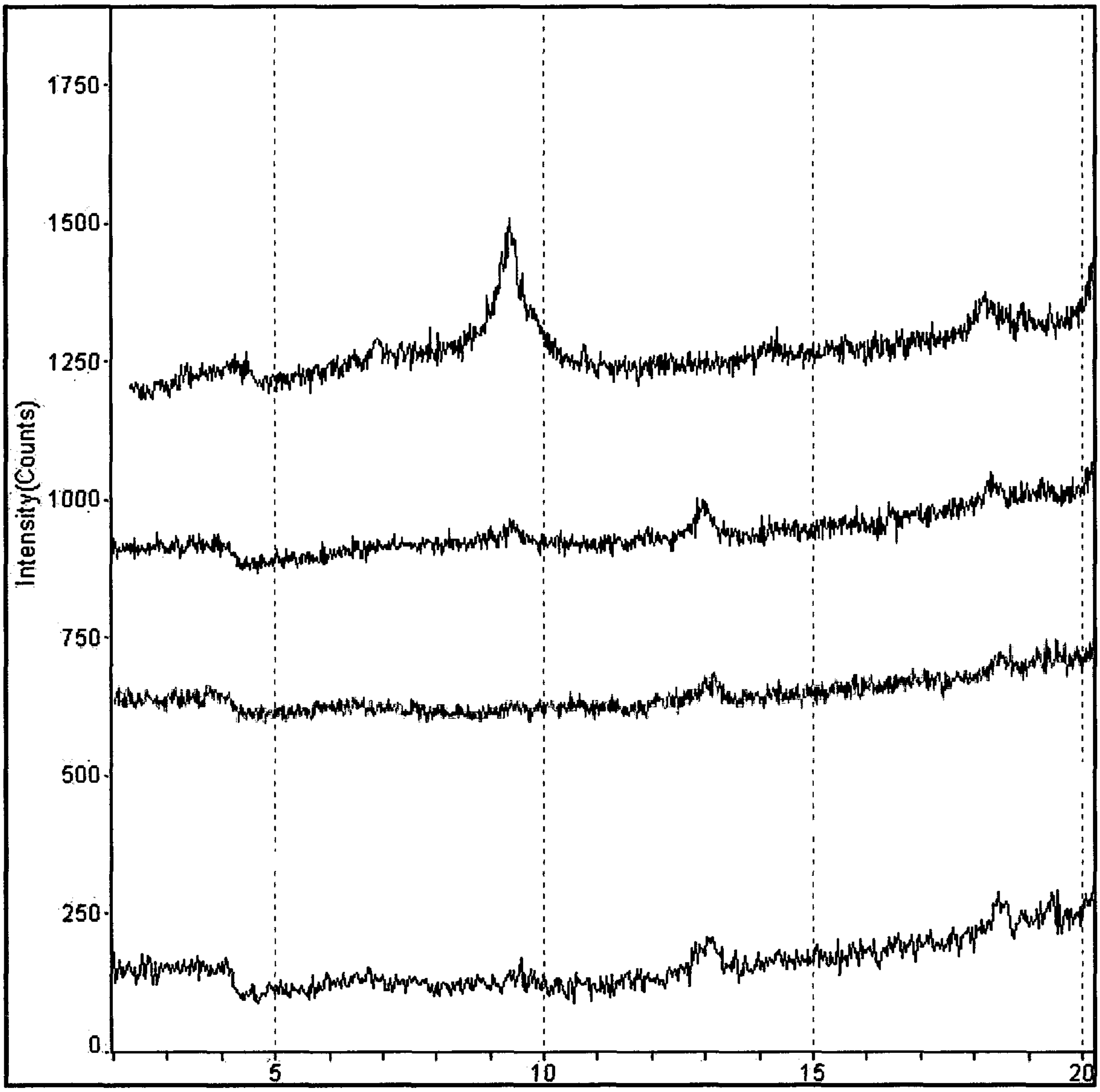

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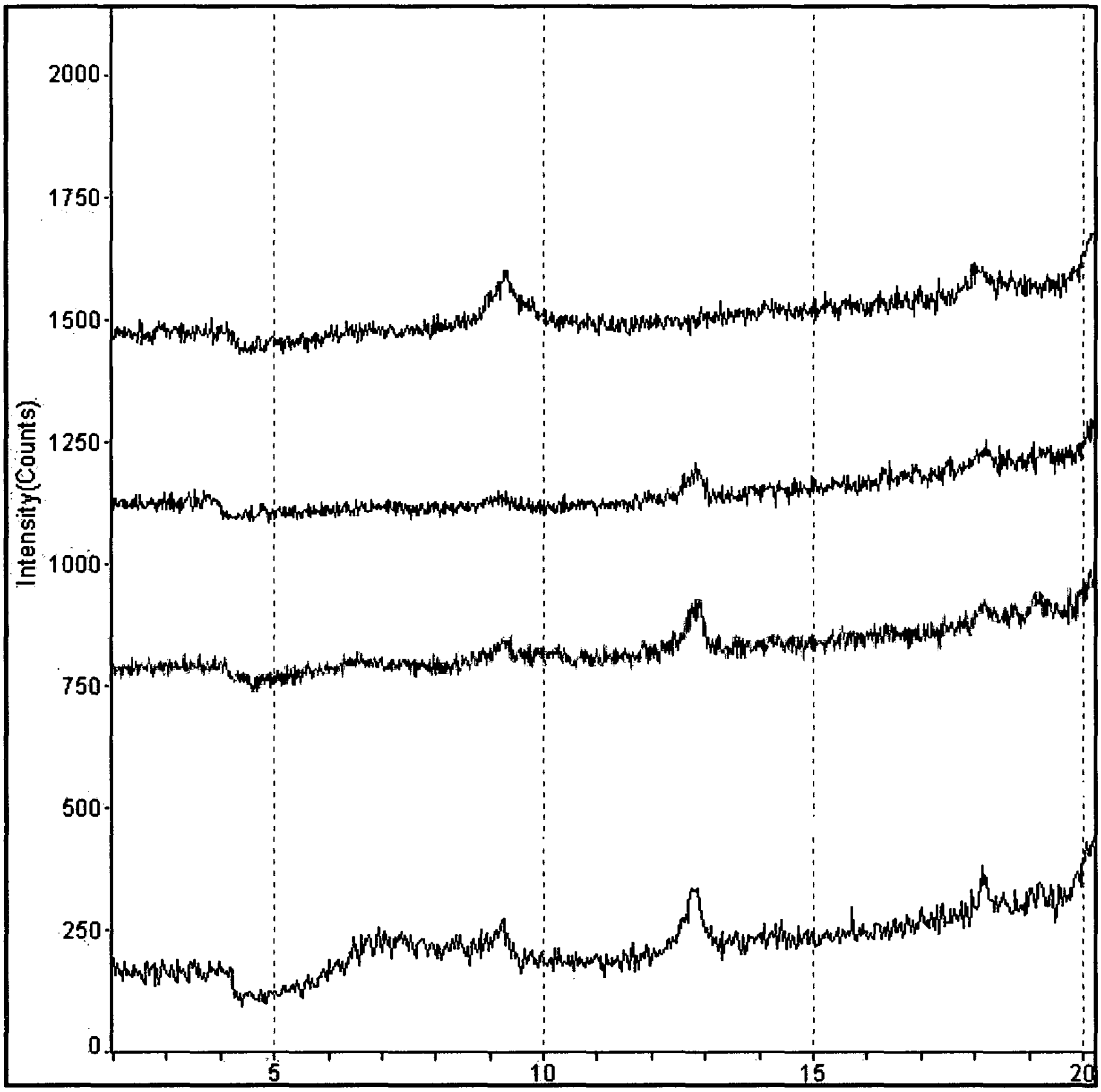
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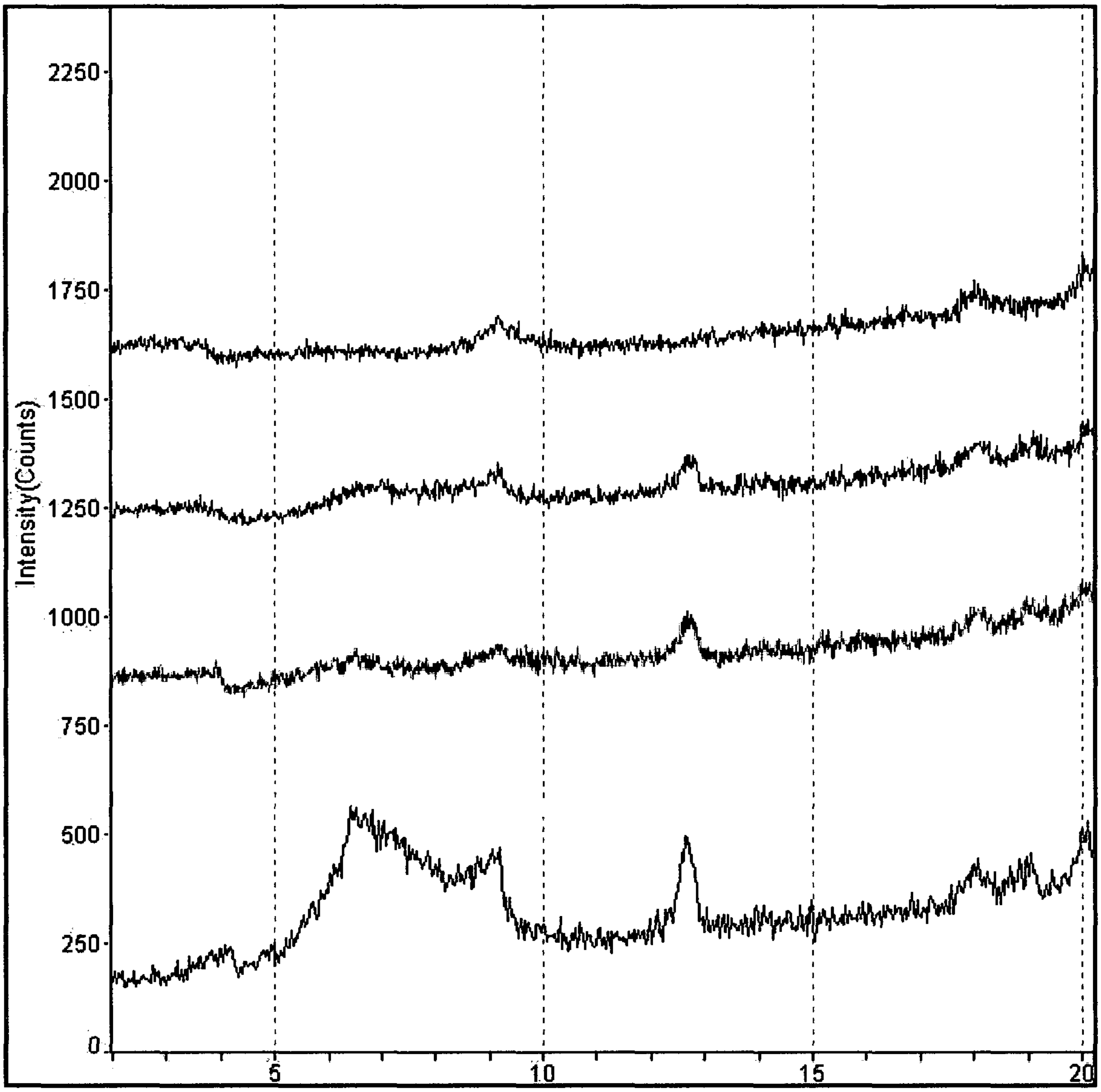

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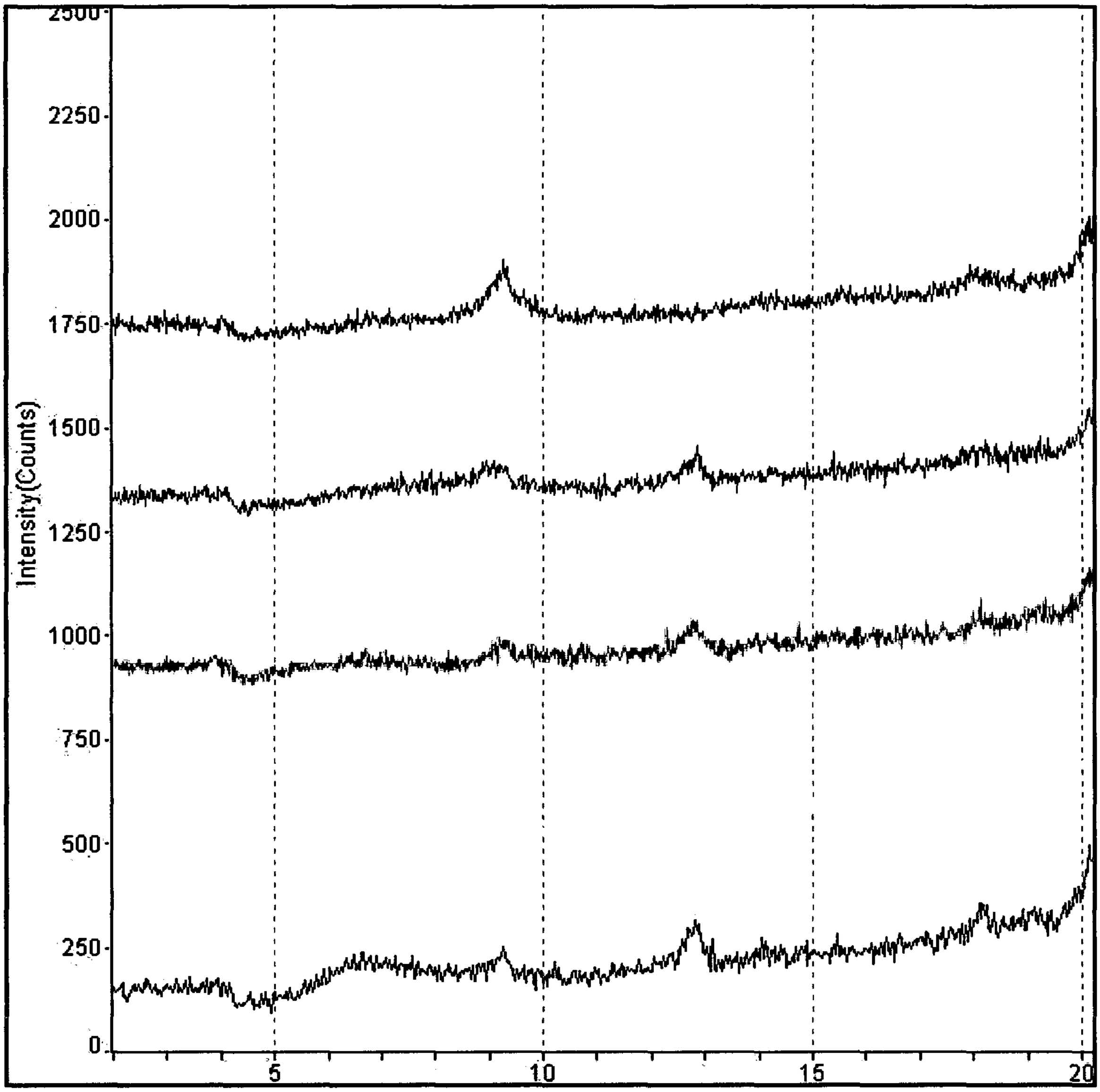
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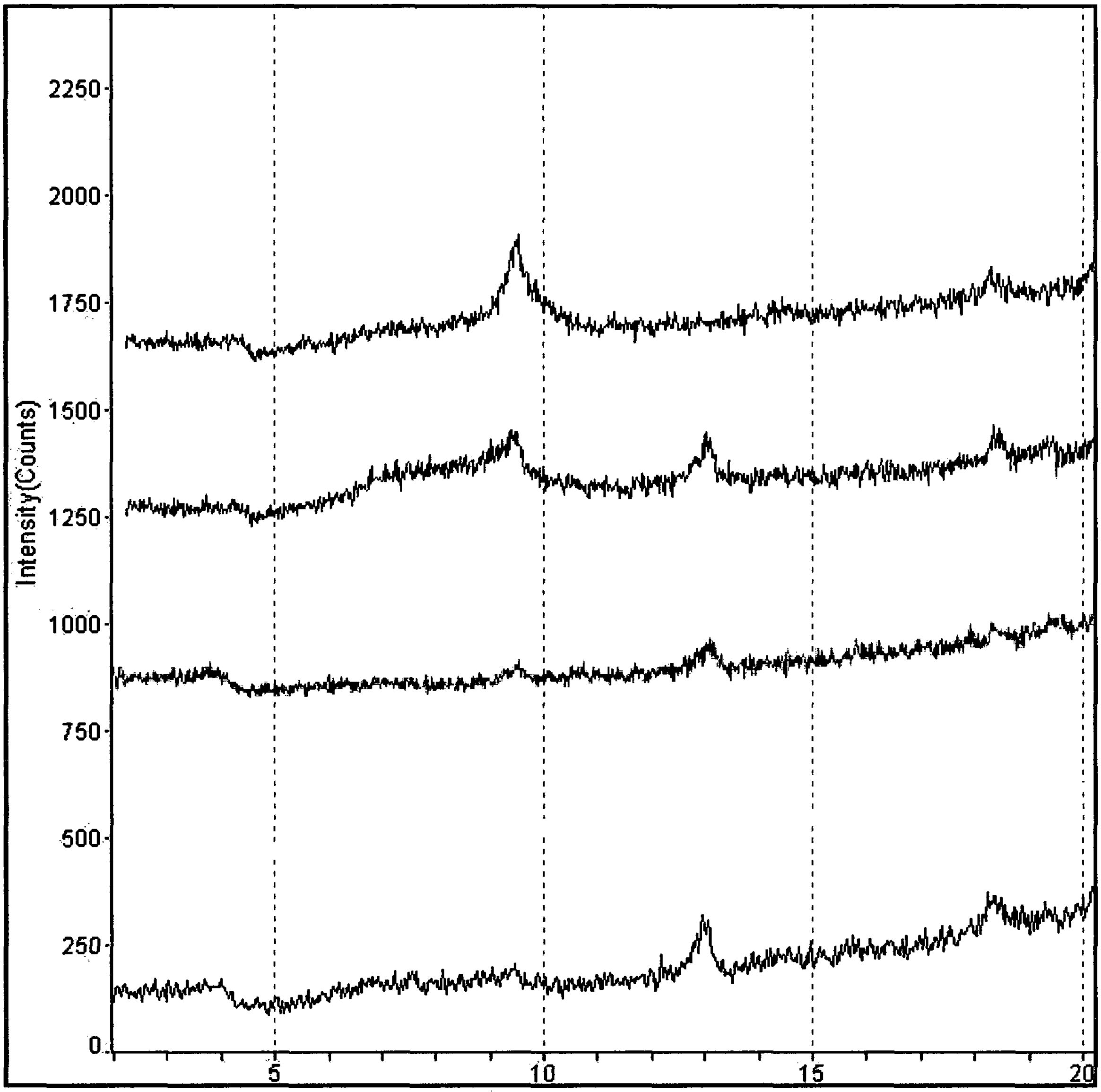
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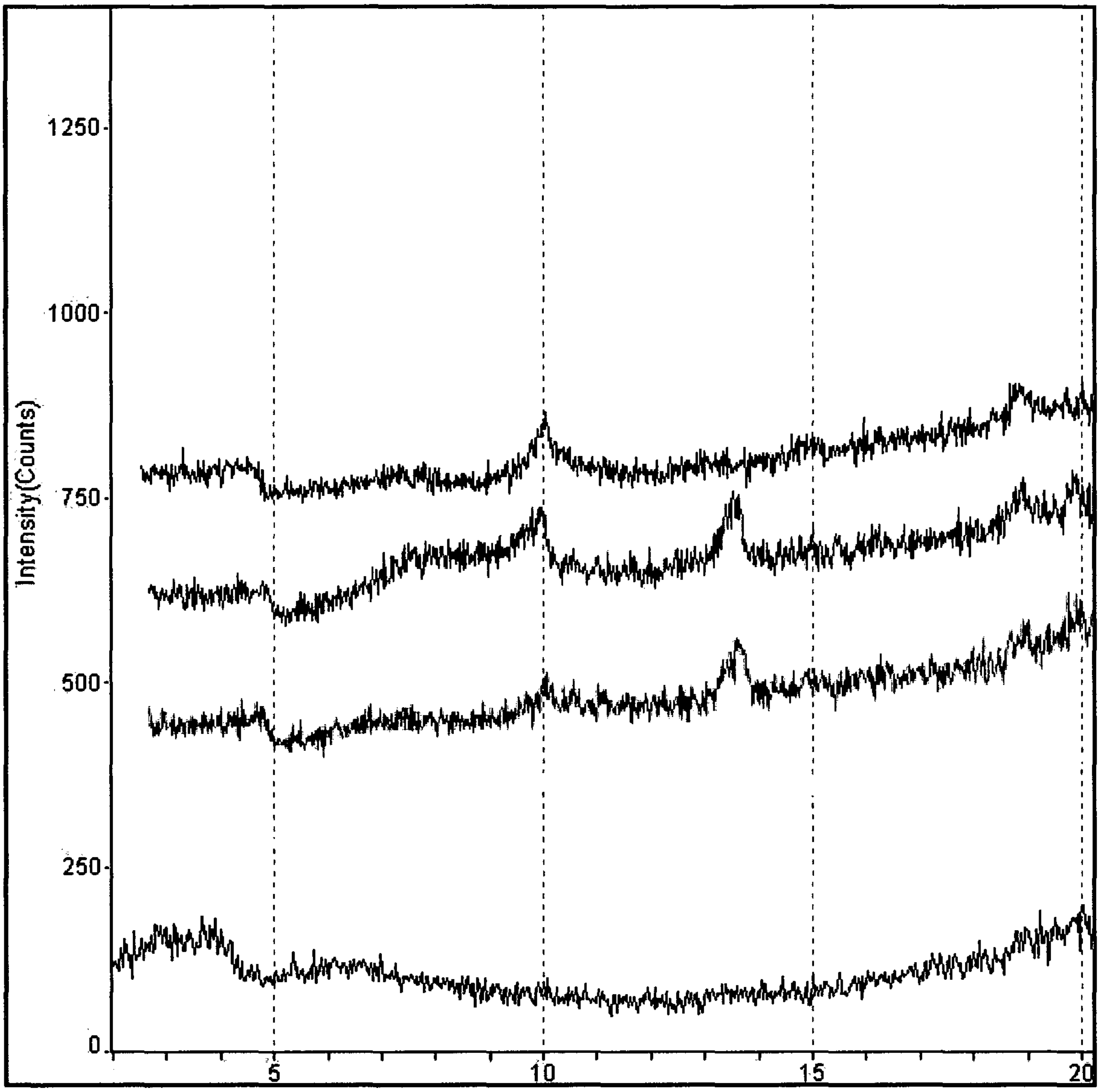

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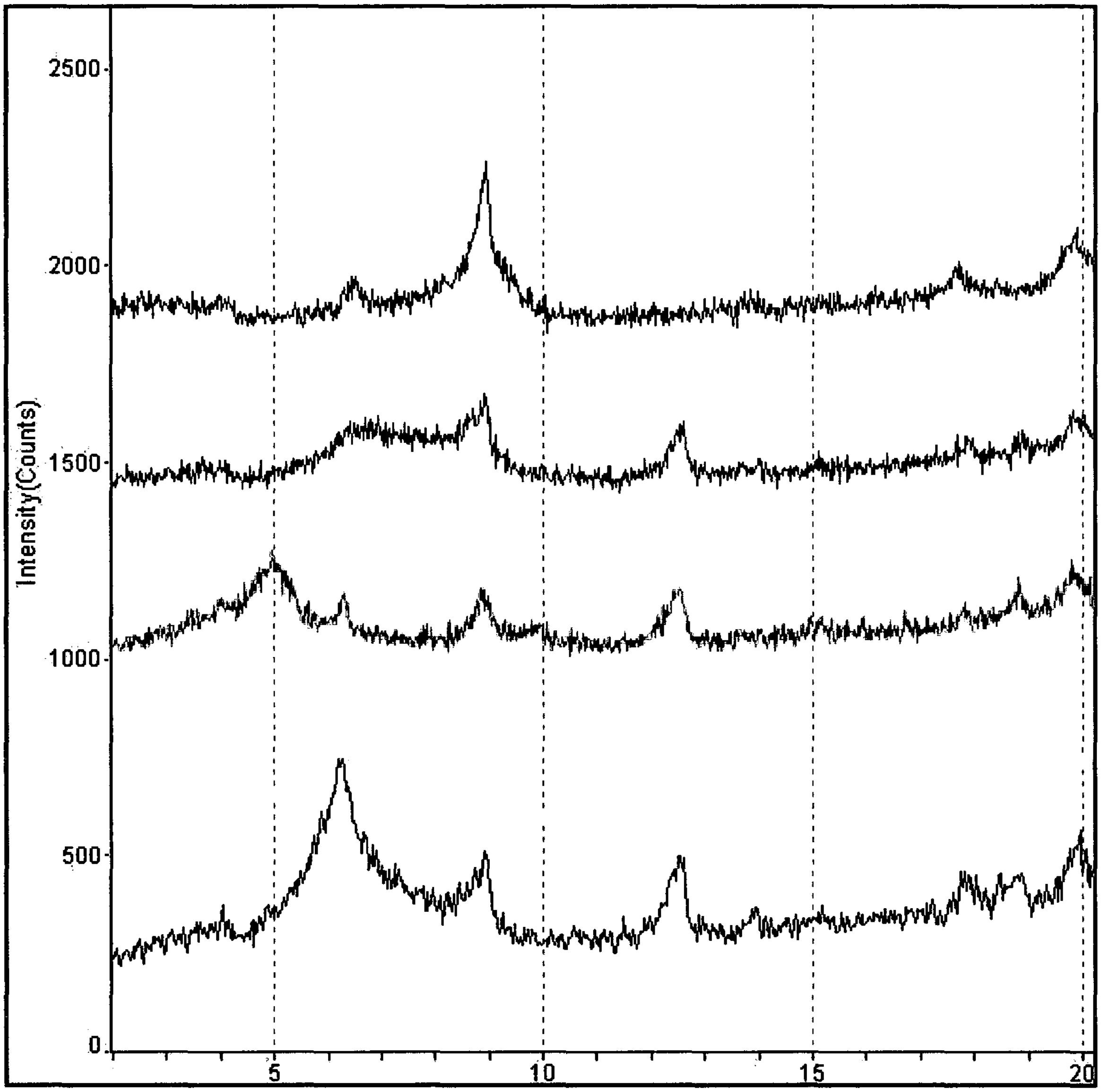

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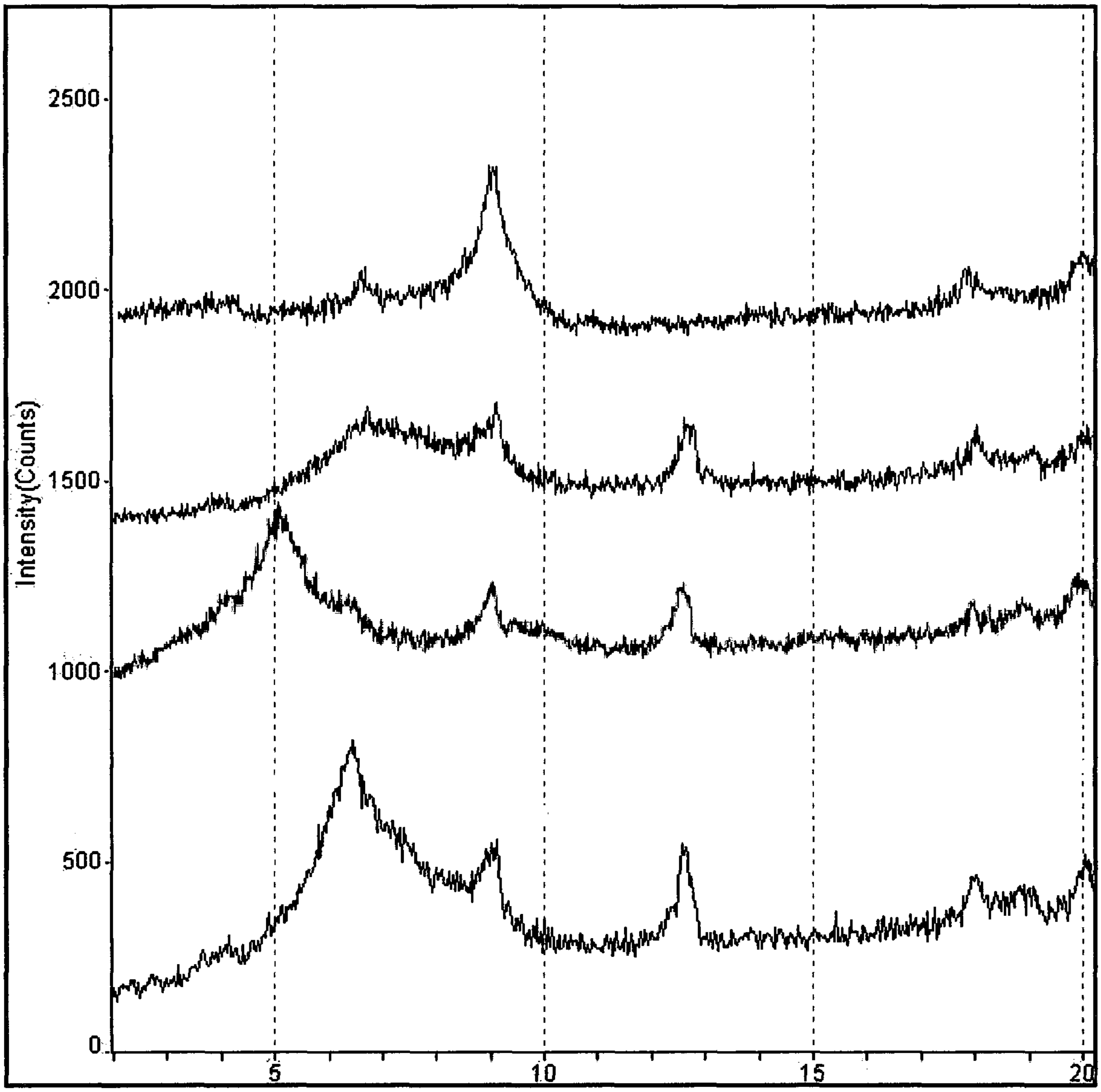

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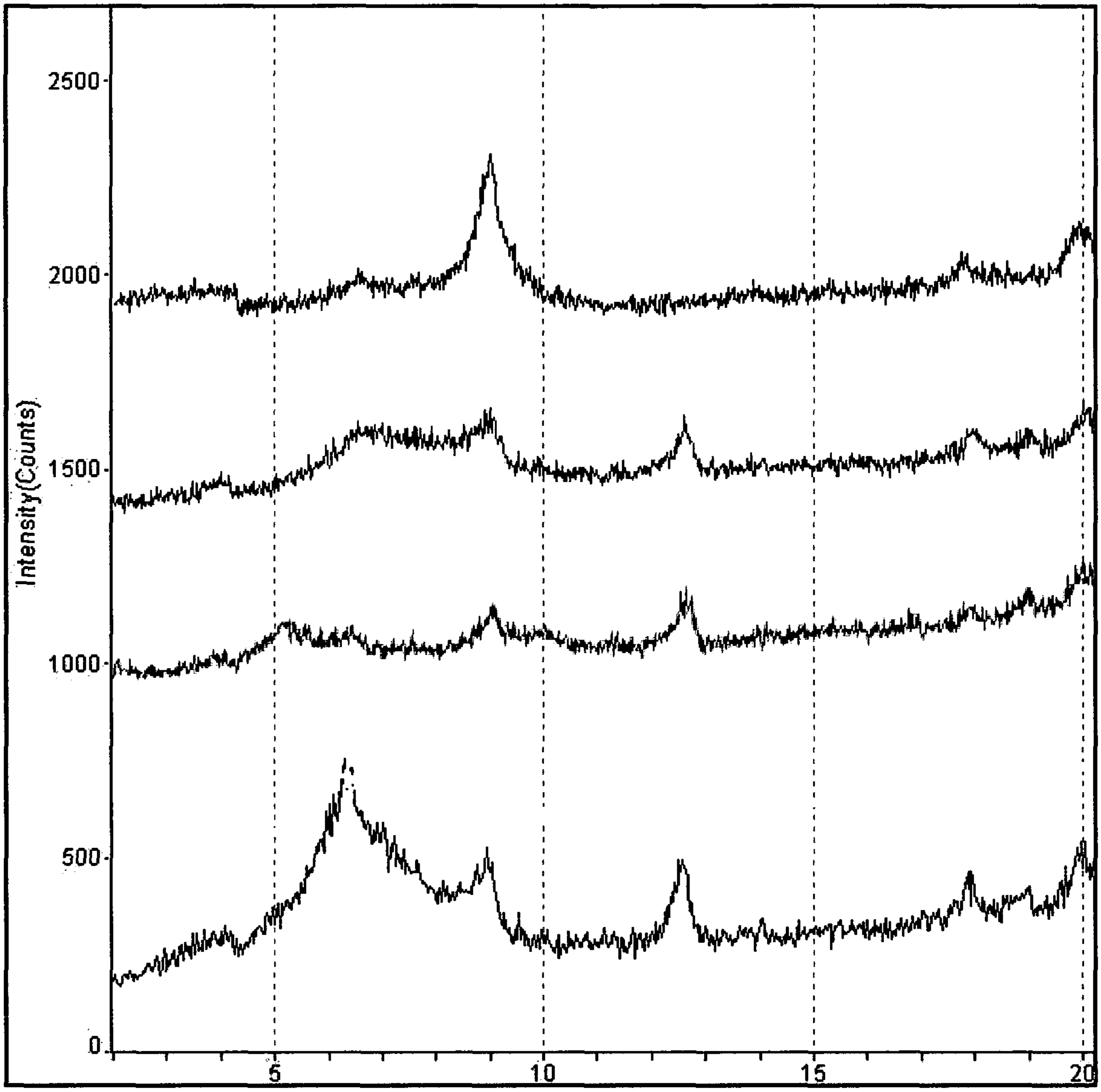

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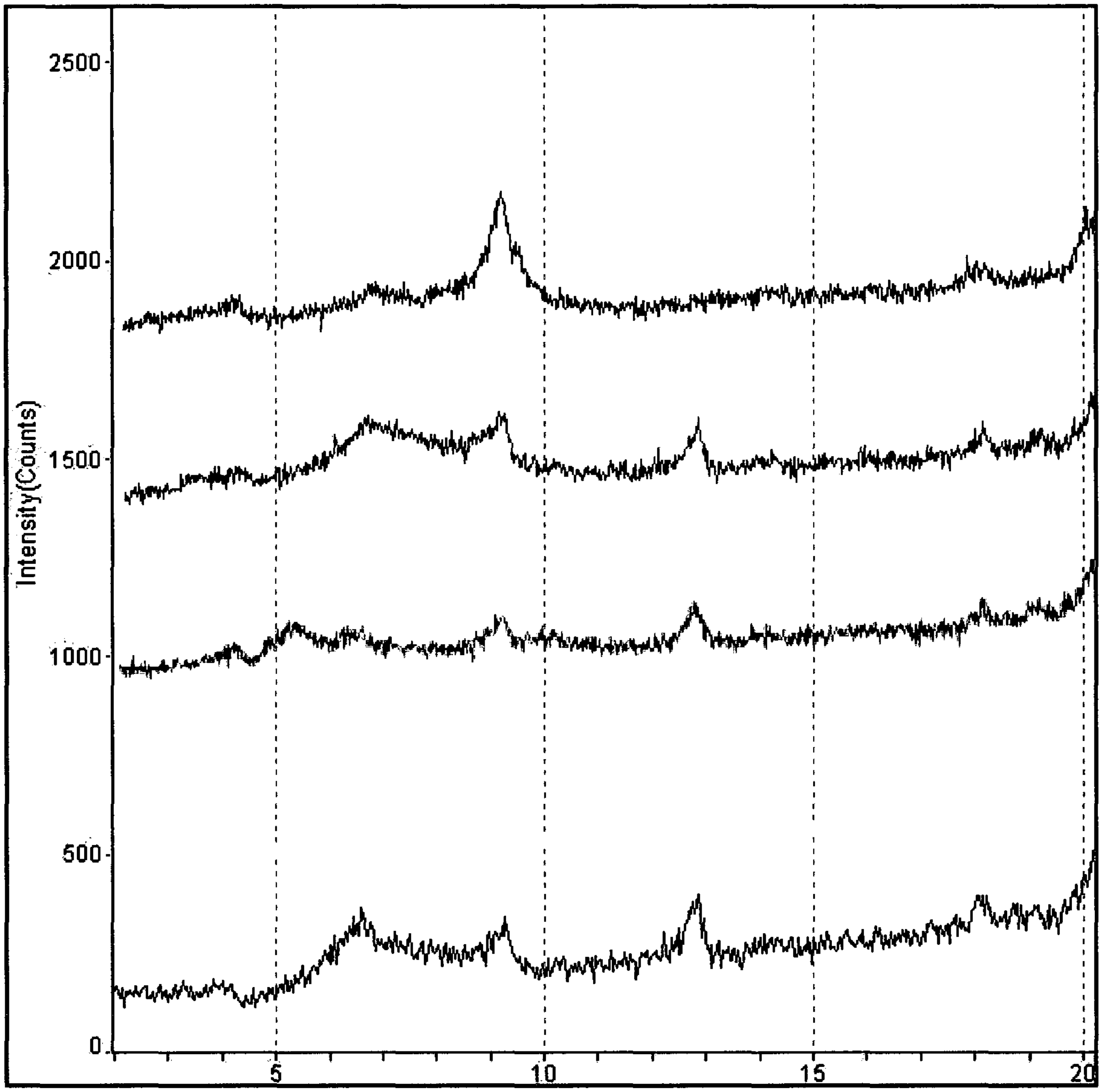

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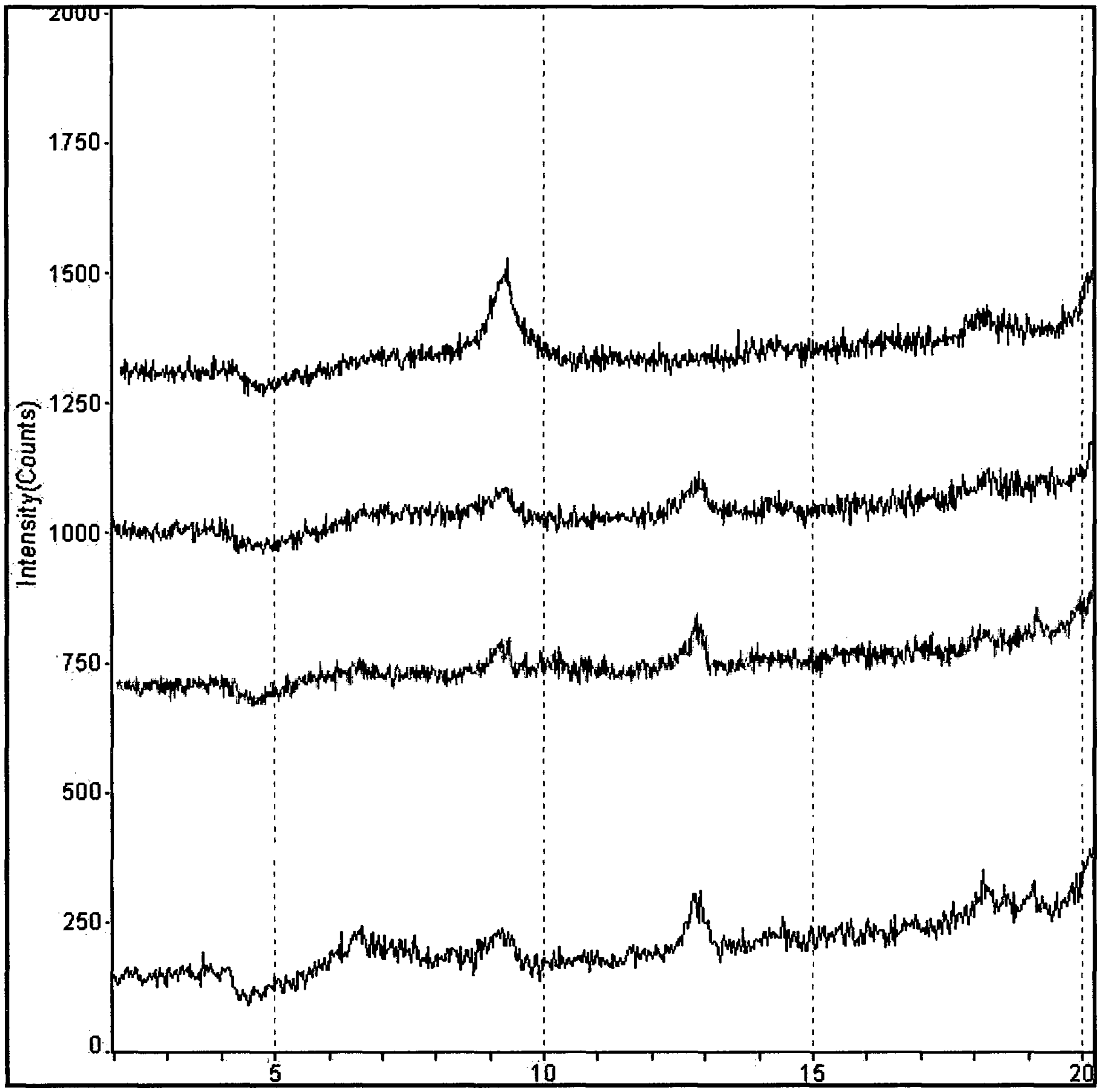
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Fid_9L_97

Louis Lake Clay Mineralogy Results

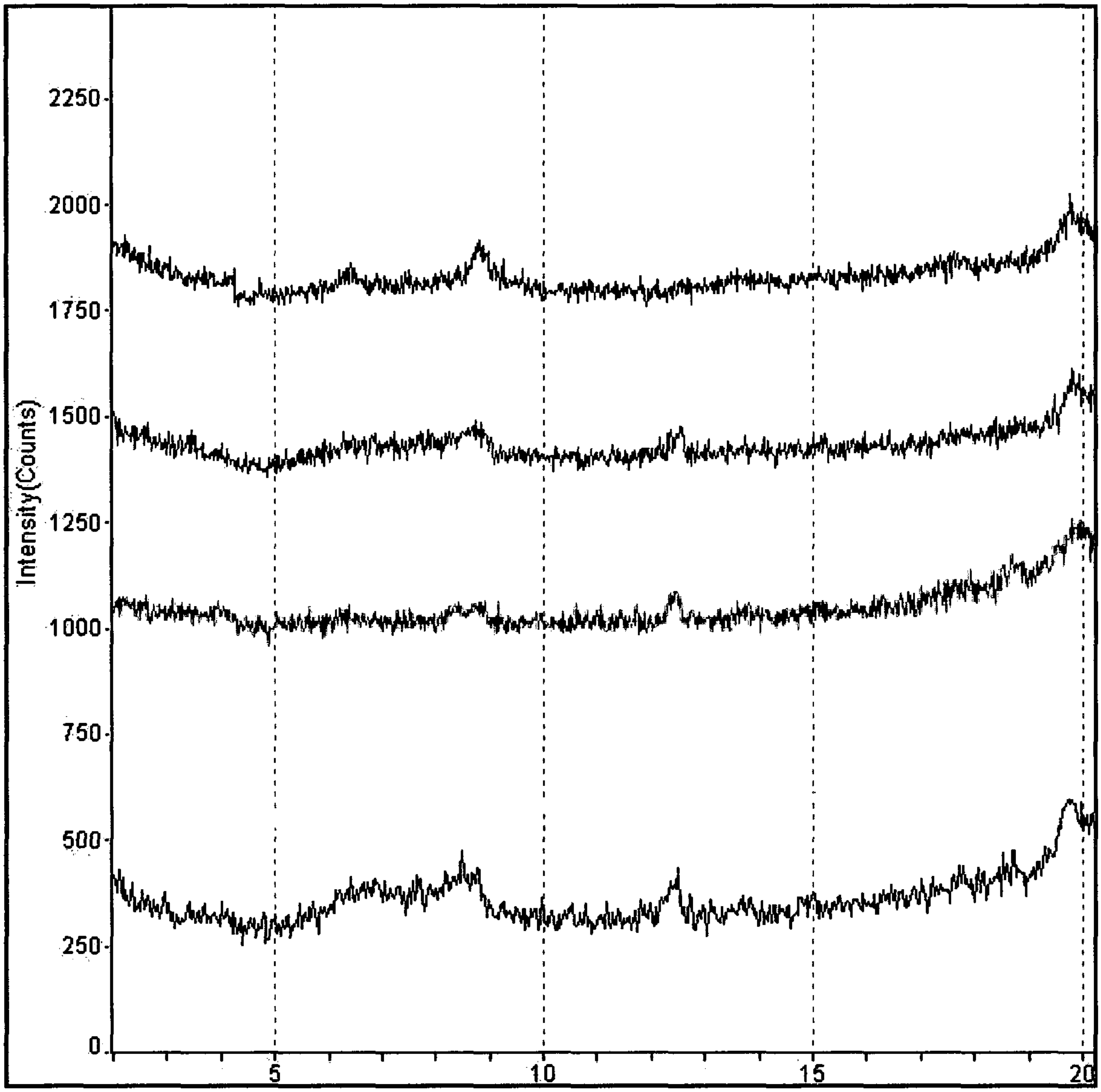
Sample	Lith. Unit	Phase	Vermiculite	Chlorite	Kaolinite	Smectite
Lou_1L_70	1	Post-Glacial	weak verm	weak chl	weak kao	
Lou_1L_80	1	Post-Glacial	weak verm		weak kao	
Lou_1L_90	1	Post-Glacial				
Lou_2L_10	1	Post-Glacial	weak verm	weak chl	weak kao	
Lou_2L_20	1	Post-Glacial	weak verm		weak kao	
Lou_2L_30	1	Post-Glacial	weak verm		weak kao	
Lou_2L_40	1	Post-Glacial	weak verm	weak chl	weak kao	
Lou_2L_50	1	Post-Glacial	weak verm		weak kao	
Lou_2L_60	1	Post-Glacial				
Lou_2L_70	1	Post-Glacial			weak kao	
Lou_2L_80	1	Post-Glacial				
Lou_2L_90	1	Post-Glacial				
Lou_2L_100	1	Post-Glacial	weak verm	weak chl	weak kao	
Lou_3L_10	1	Post-Glacial			weak kao	
Lou_3L_20	1	Post-Glacial				
Lou_3L_30	1	Post-Glacial				
Lou_3L_40	1	Post-Glacial				
Lou_3L_50	1	Post-Glacial	weak verm	weak chl	kao	
Lou_3L_60	1	Post-Glacial				
Lou_3L_70	1	Post-Glacial				
Lou_3L_80	1	Post-Glacial				
Lou_4L_02	1	Post-Glacial				
Lou_4L_12	1	Post-Glacial				
Lou_4L_22	1	Post-Glacial	weak verm	weak chl	weak kao	
Lou_4L_32	1	Post-Glacial				
Lou_4L_42	1	Transitional	weak verm			
Lou_4L_52	1	Transitional				
Lou_4L_62	1	Transitional			weak kao	
Lou_4L_72	1	Transitional	weak verm	weak chl	weak kao	
Lou_4L_82	2	Transitional				
Lou_4L_92	2	Transitional	verm		kao	
Lou_4L_102	2	Transitional			weak kao	
Lou_5L_11	2	Late-Glacial			kao	
Lou_5L_21	2	Late-Glacial	weak verm		kao	
Lou_5L_31	3	Late-Glacial	verm	weak chl	kao	
Lou_5L_41	3	Late-Glacial	verm		kao	
Lou_5L_51	3	Late-Glacial			weak kao	
Lou_5L_61	3	Full-Glacial	verm	weak chl	kao	weak smec

(table continues)

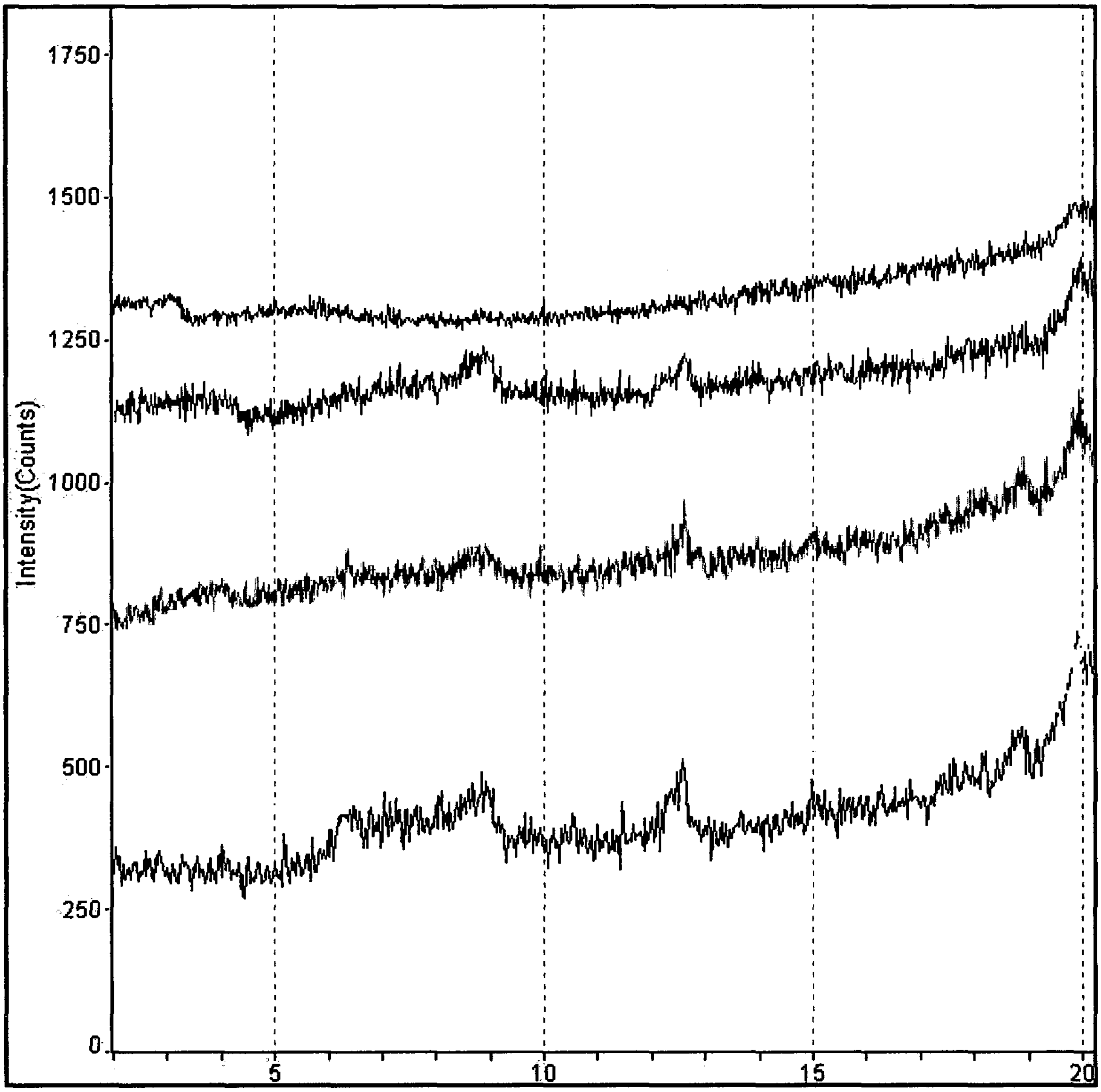
Sample	Lith. Unit	Phase	Vermiculite	Chlorite	Kaolinite	Smectite
Lou_5L_71	3	Full-Glacial			kao	
Lou_5L_81	3	Full-Glacial			kao	
Lou_5L_91	3	Full-Glacial			kao	
Lou_6L_09	3	Full-Glacial			weak kao	
Lou_6L_29	4	Full-Glacial		weak chl	kao	
Lou_6L_49	4	Full-Glacial			kao	
Lou_6L_69	4	Full-Glacial	verm	weak chl	kao	smec
Lou_6L_89	4	Full-Glacial	verm	weak chl	kao	smec
Lou_7L_13	4	Full-Glacial			kao	
Lou_7L_33	4	Full-Glacial			kao	
Lou_7L_53	4	Full-Glacial	verm	weak chl	kao	
Lou_7L_73	4	Full-Glacial			kao	
Lou_7L_93	4	Full-Glacial	verm	weak chl	kao	smec
Lou_8L_59	4	Full-Glacial	verm	weak chl	kao	weak smec
Lou_8L_79	4	Full-Glacial	verm	weak chl	kao	smec
Lou_8L_99	4	Full-Glacial	verm	weak chl	kao	smec
Lou_9L_30	4	Full-Glacial	verm	weak chl	kao	weak smec
Lou_9L_50	4	Full-Glacial	verm	weak chl	kao	smec
Lou_9L_70	4	Full-Glacial	verm		kao	
Lou_9L_90	4	Full-Glacial	verm	weak chl	kao	smec
Lou_10L_26	4	Full-Glacial	verm	weak chl	kao	weak smec
Lou_10L_46	4	Full-Glacial	verm	weak chl	kao	
Lou_10L_66	4	Full-Glacial	verm		kao	smec
Lou_10L_86	4	Full-Glacial	verm		kao	smec
Lou_11L_31	4	Full-Glacial	verm		kao	smec
Lou_11L_51	4	Full-Glacial			kao	
Lou_11L_71	4	Full-Glacial	verm	weak chl	kao	smec
Lou_11L_91	4	Full-Glacial	verm	weak chl	kao	weak smec

<u>Louis Lake Clay Peak Traces</u>

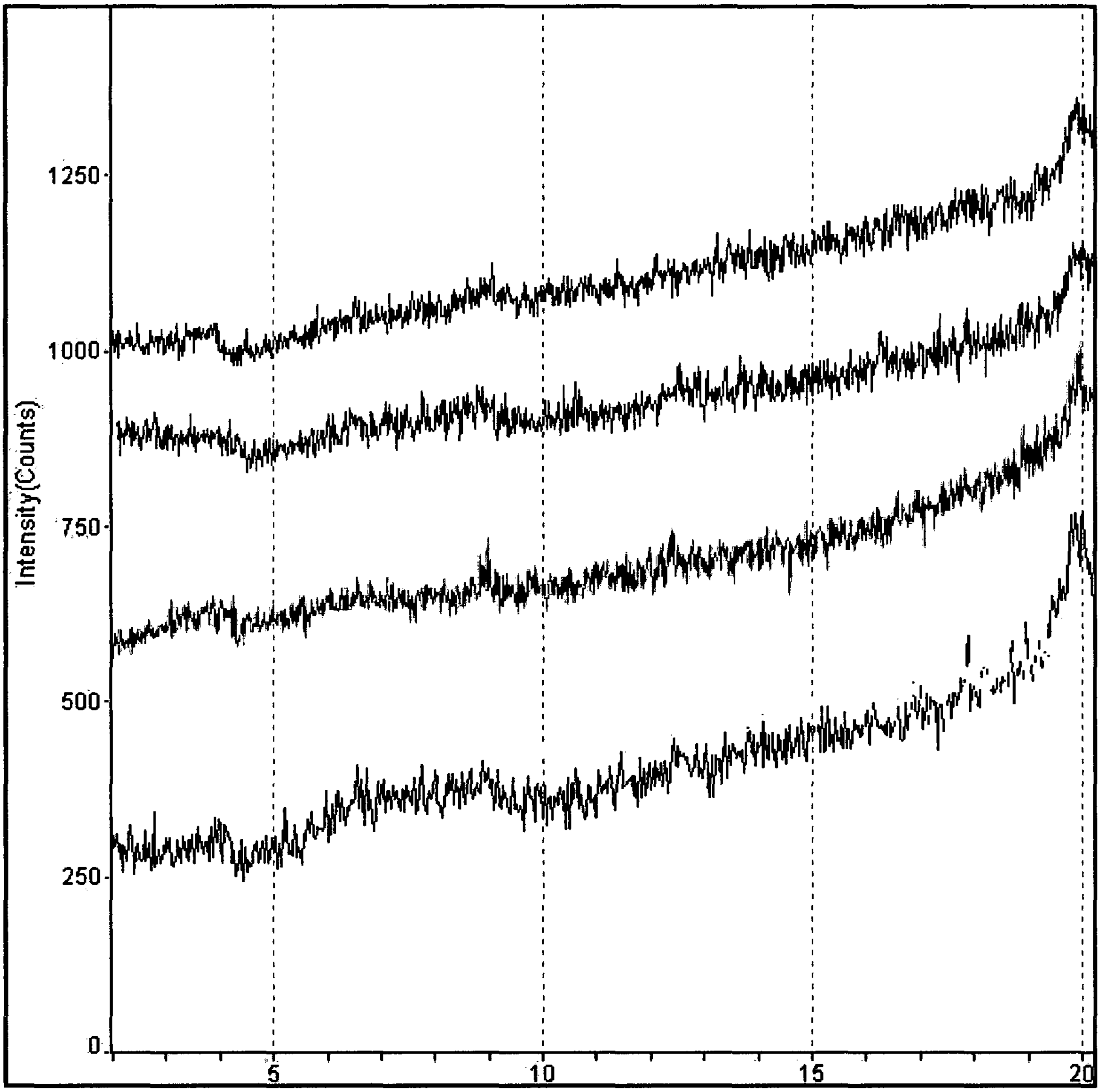
Traces are stacked vertically from bottom to top in order of successive pretreatment: air-dry, magnesium-chloride, glycerol, 300°C and 550°C.



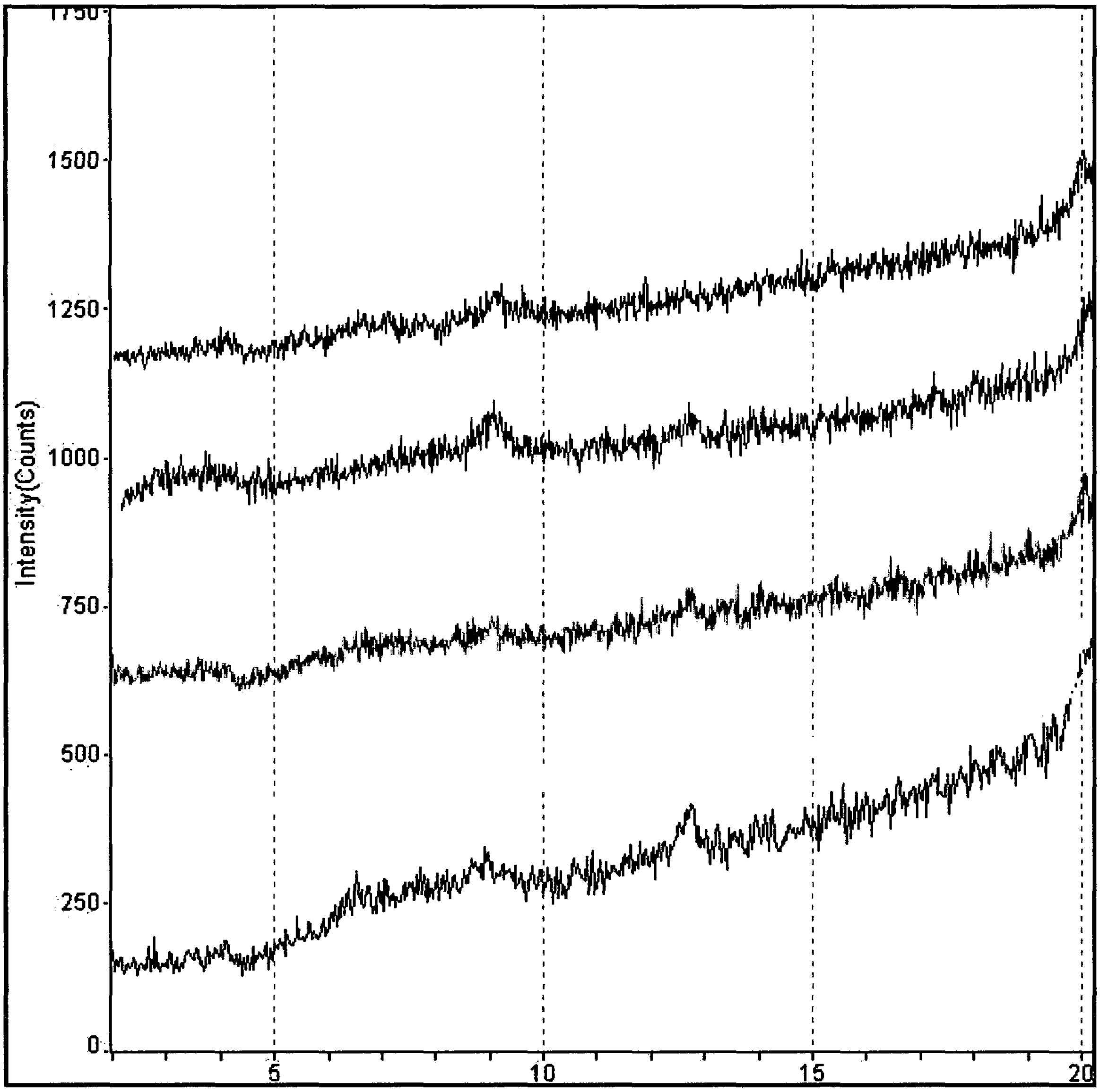
Lou_1L_70



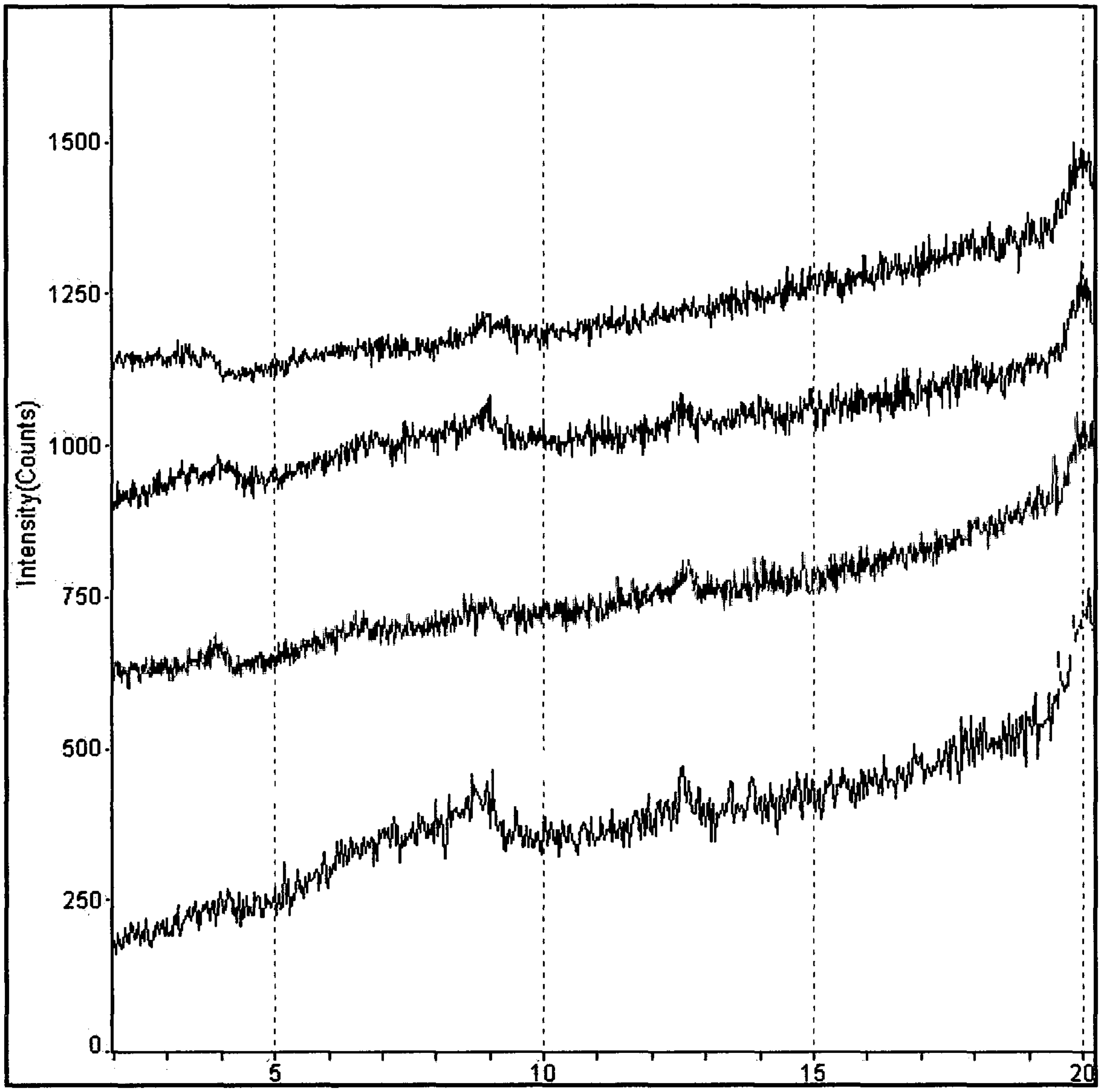
Lou_1L_80



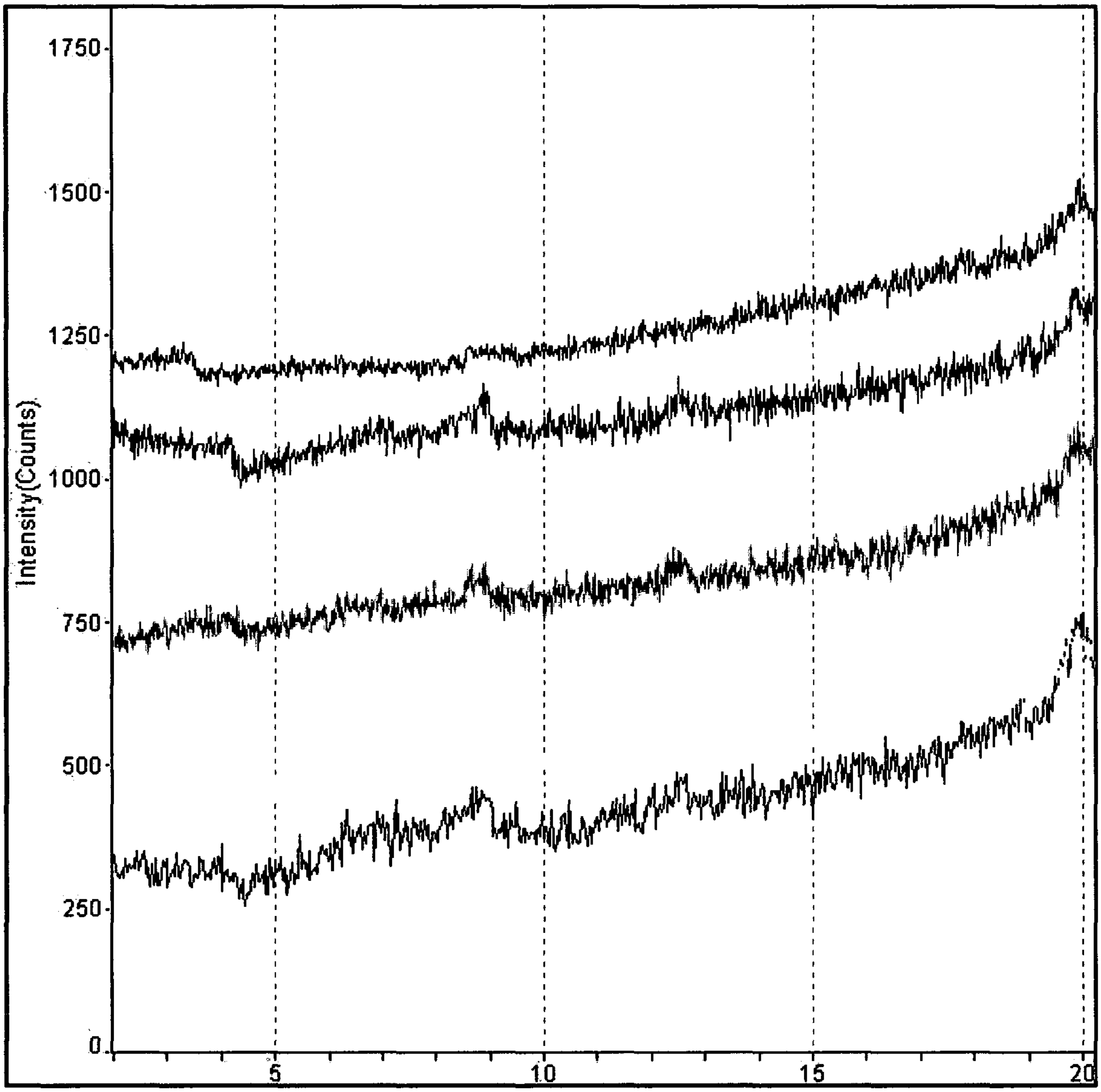
Lou_1L_90



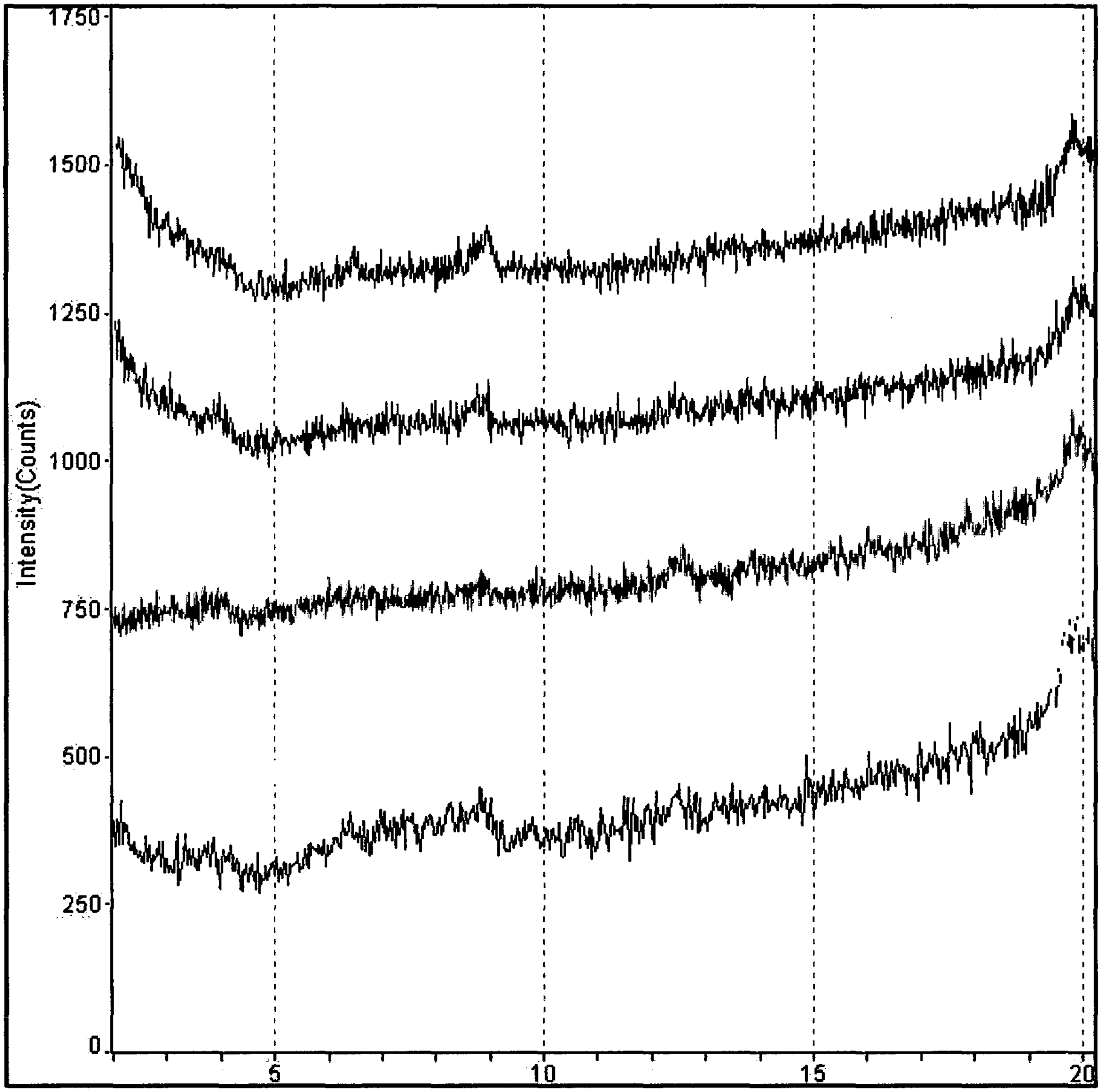
Lou_2L_10



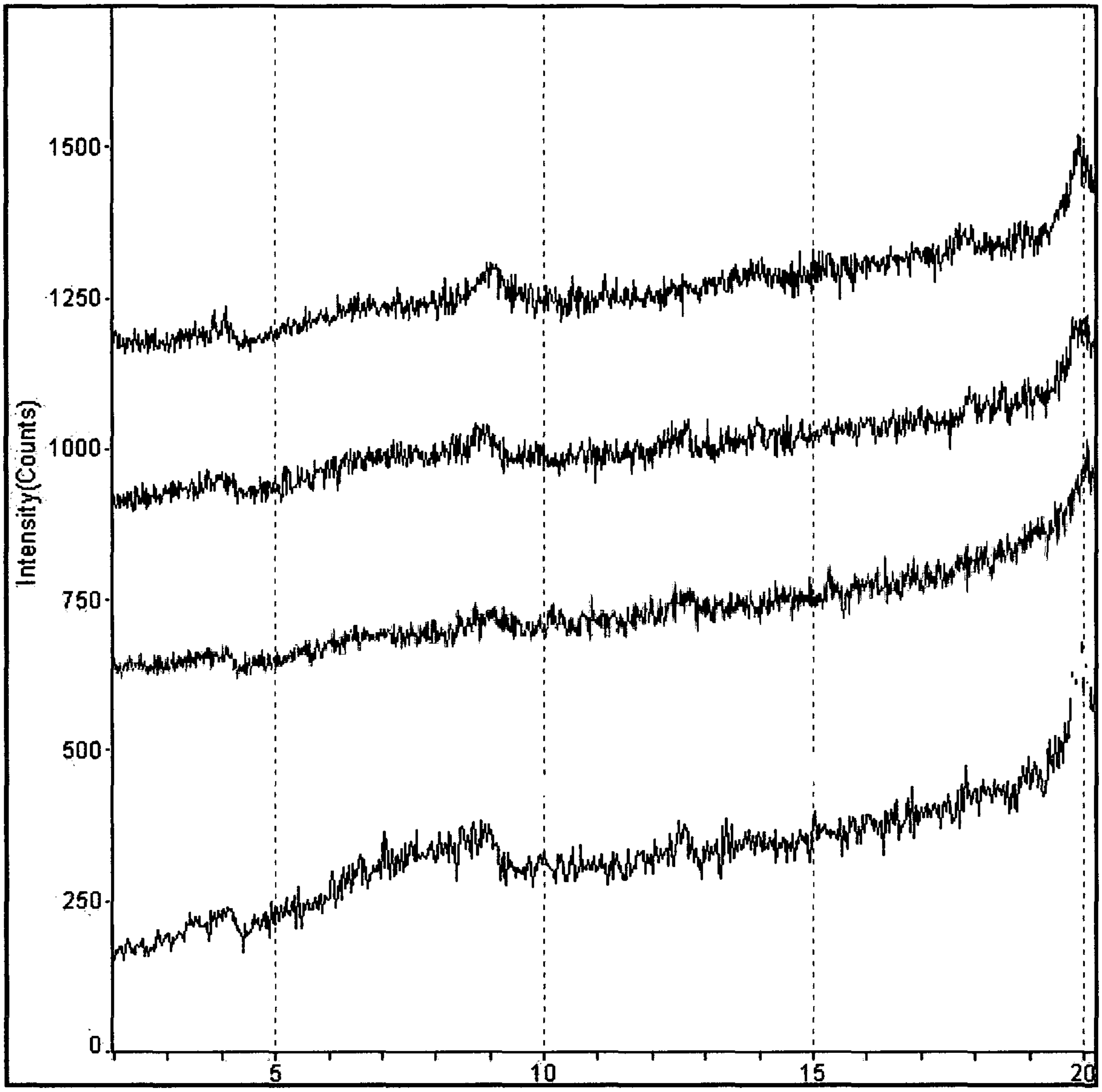
Lou_2L_20



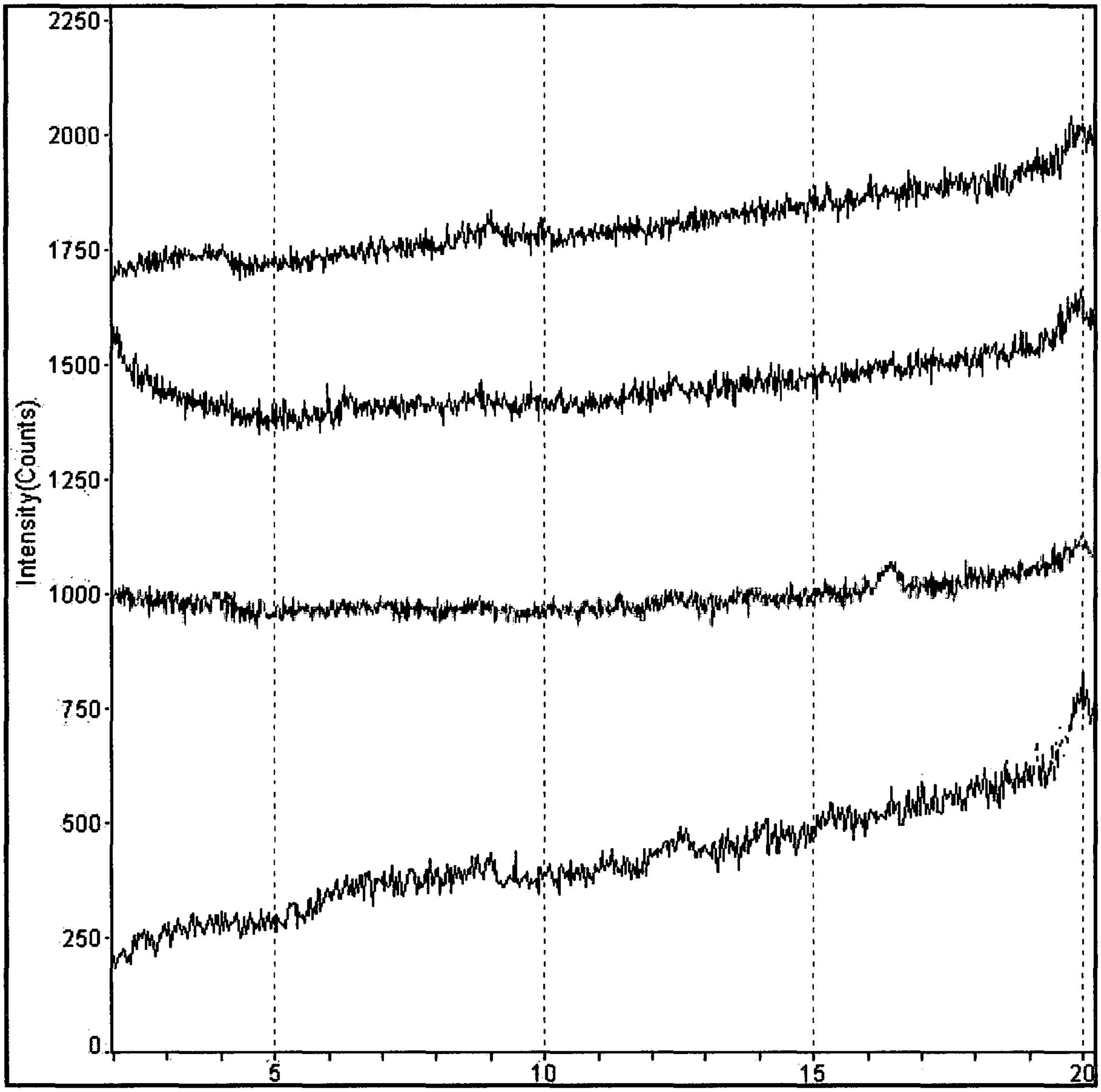
Lou_2L_30



Lou_2L_40



Lou_2L_50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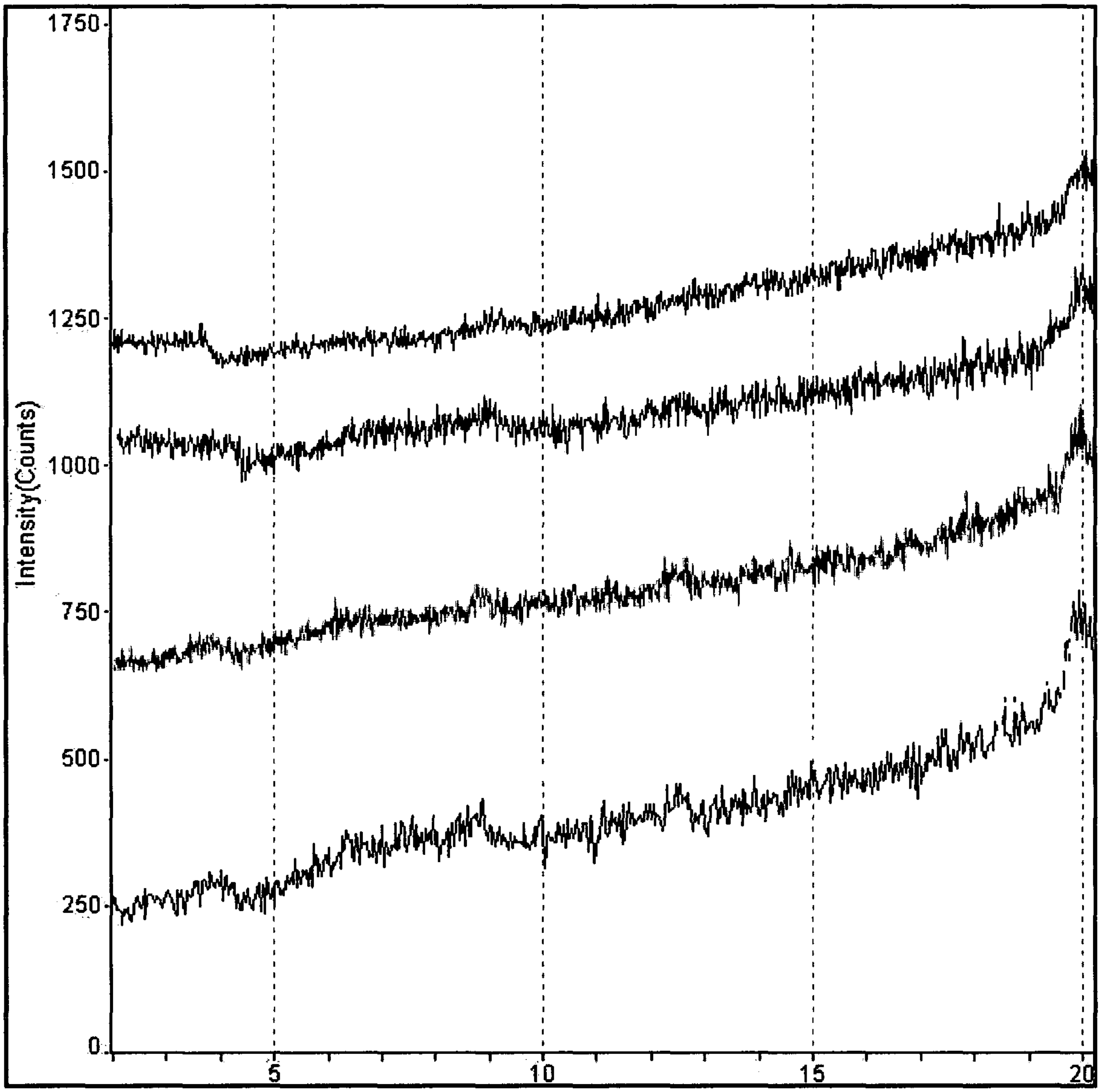
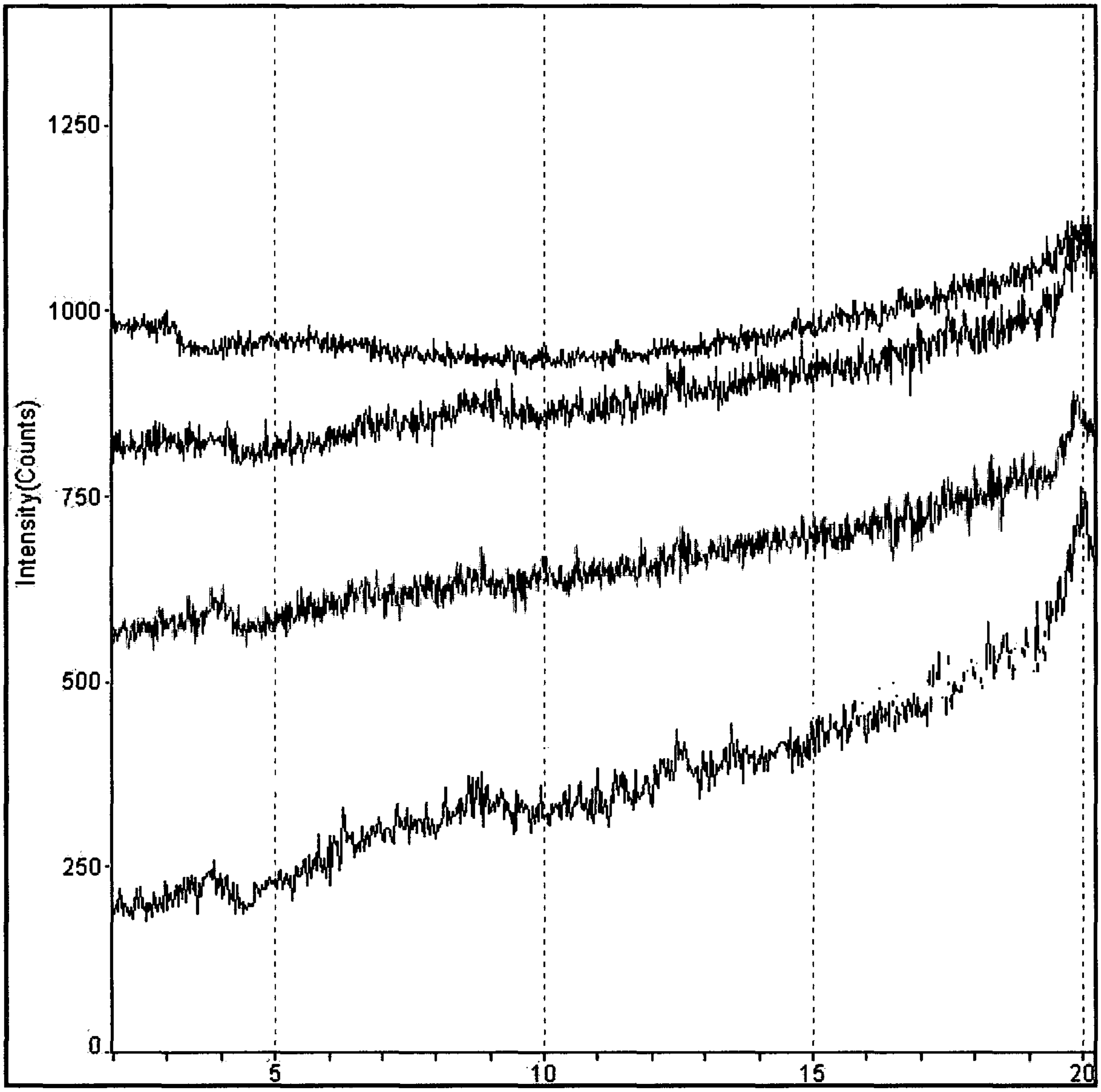
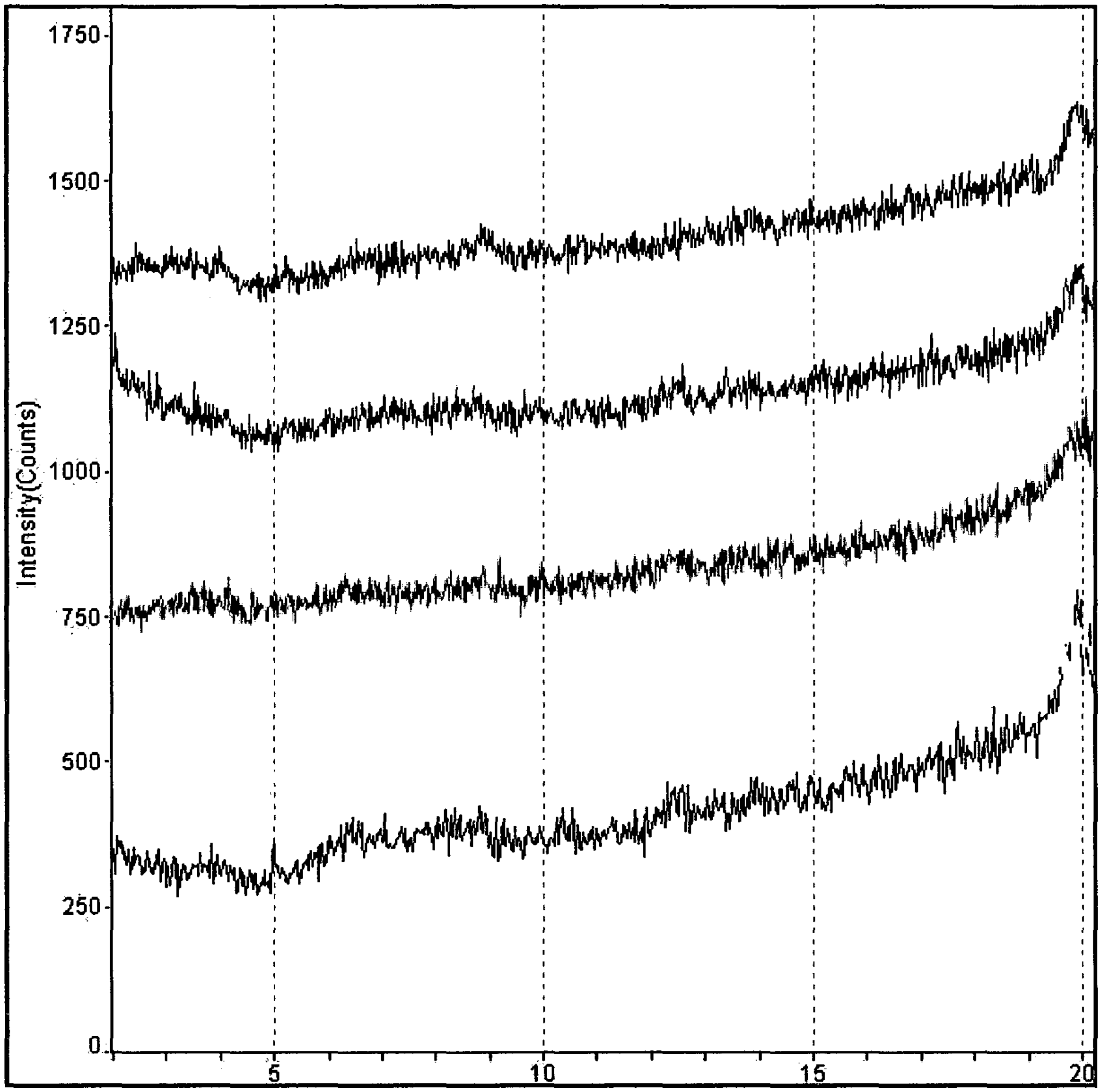
Lou_2L_60



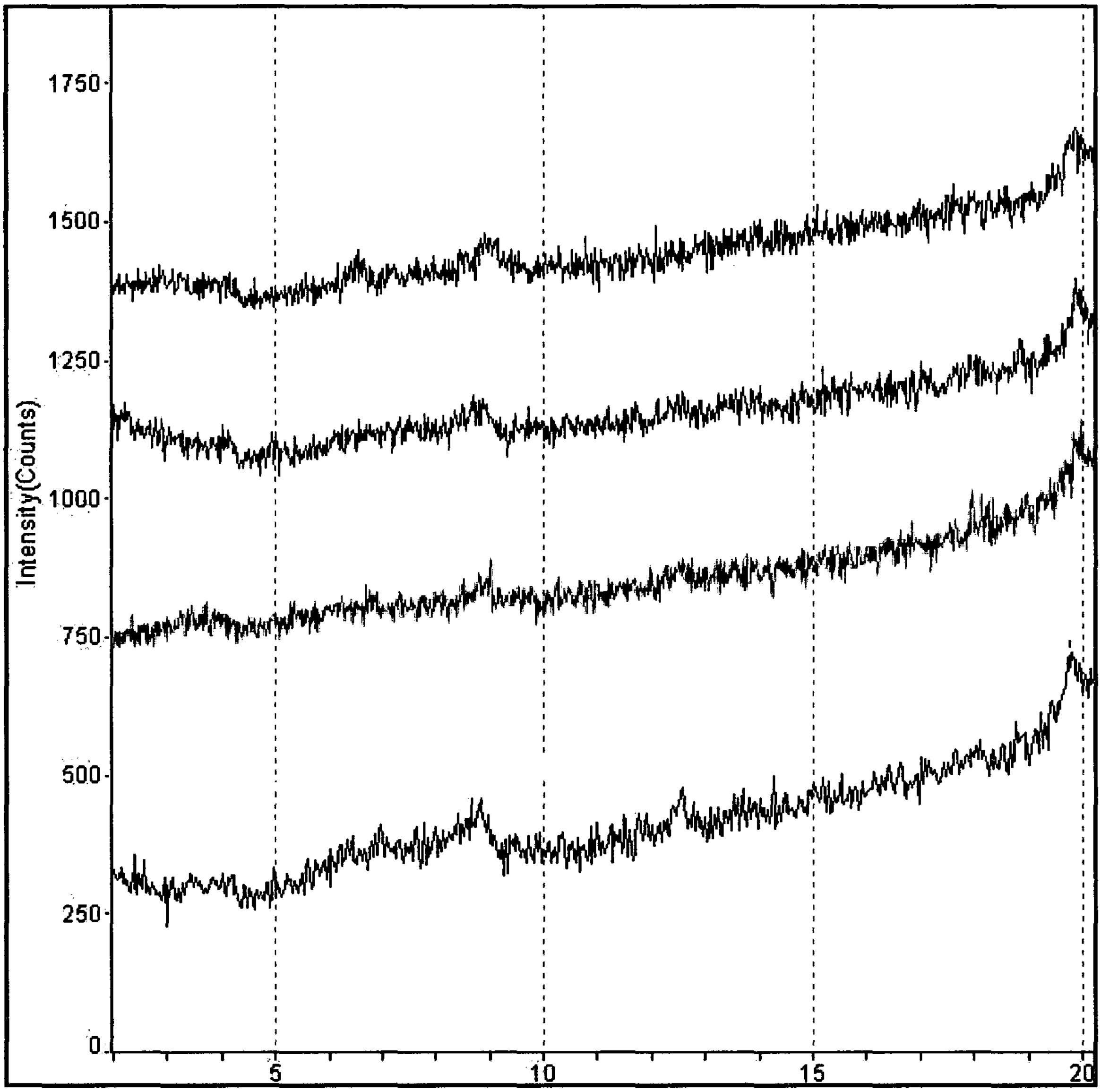
Lou_2L_70



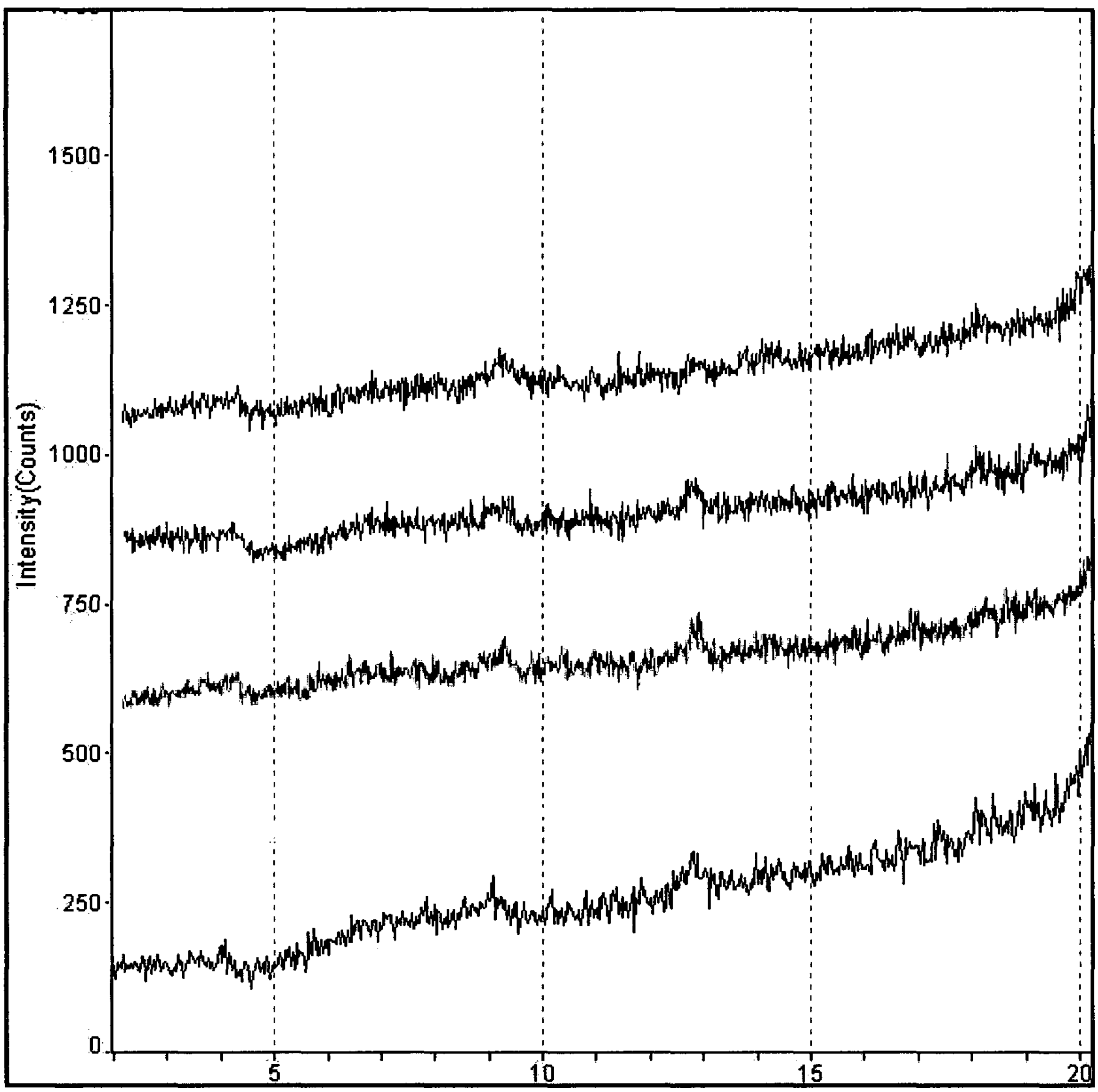
Lou_2L_80



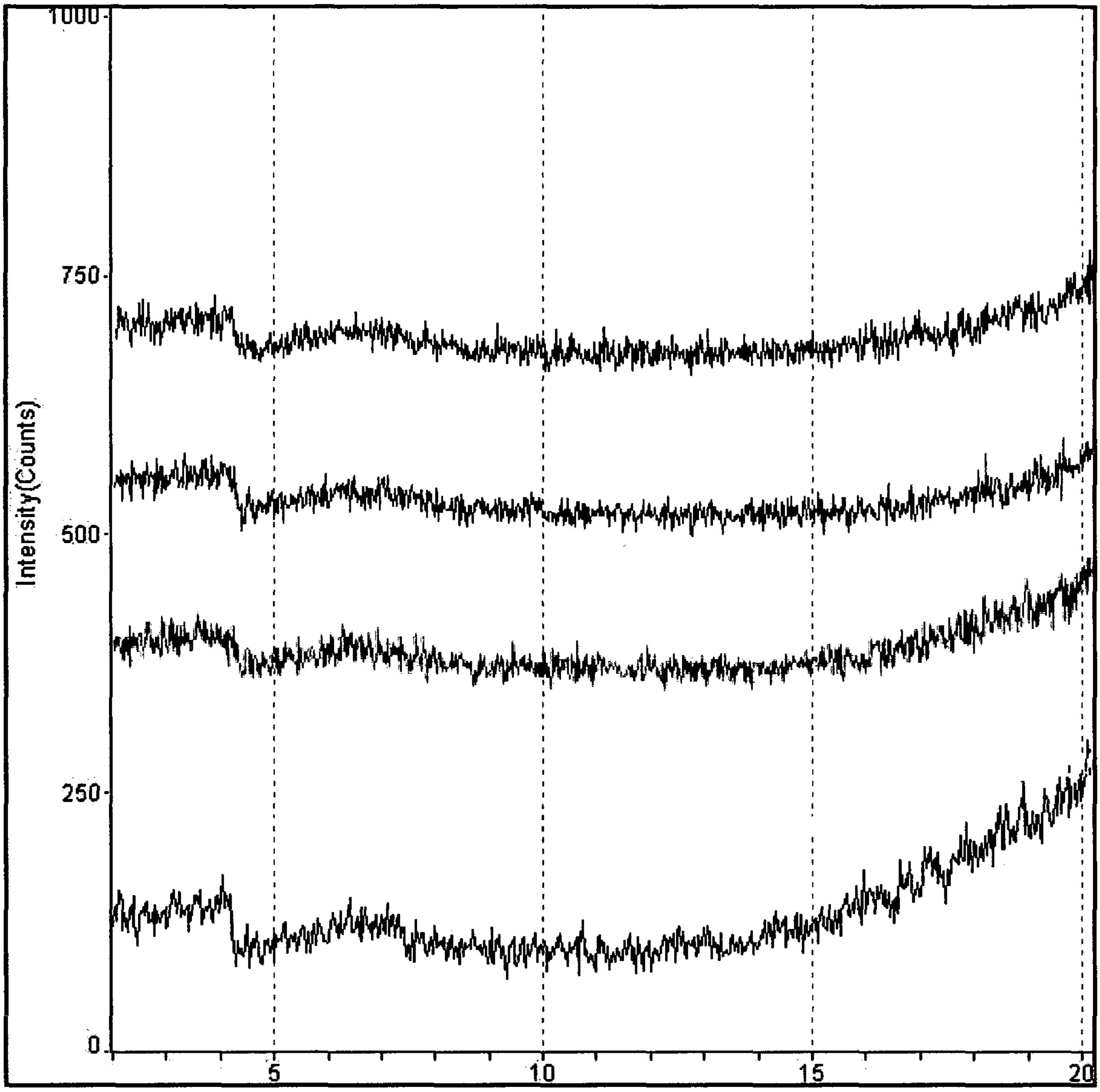
Lou_2L_90



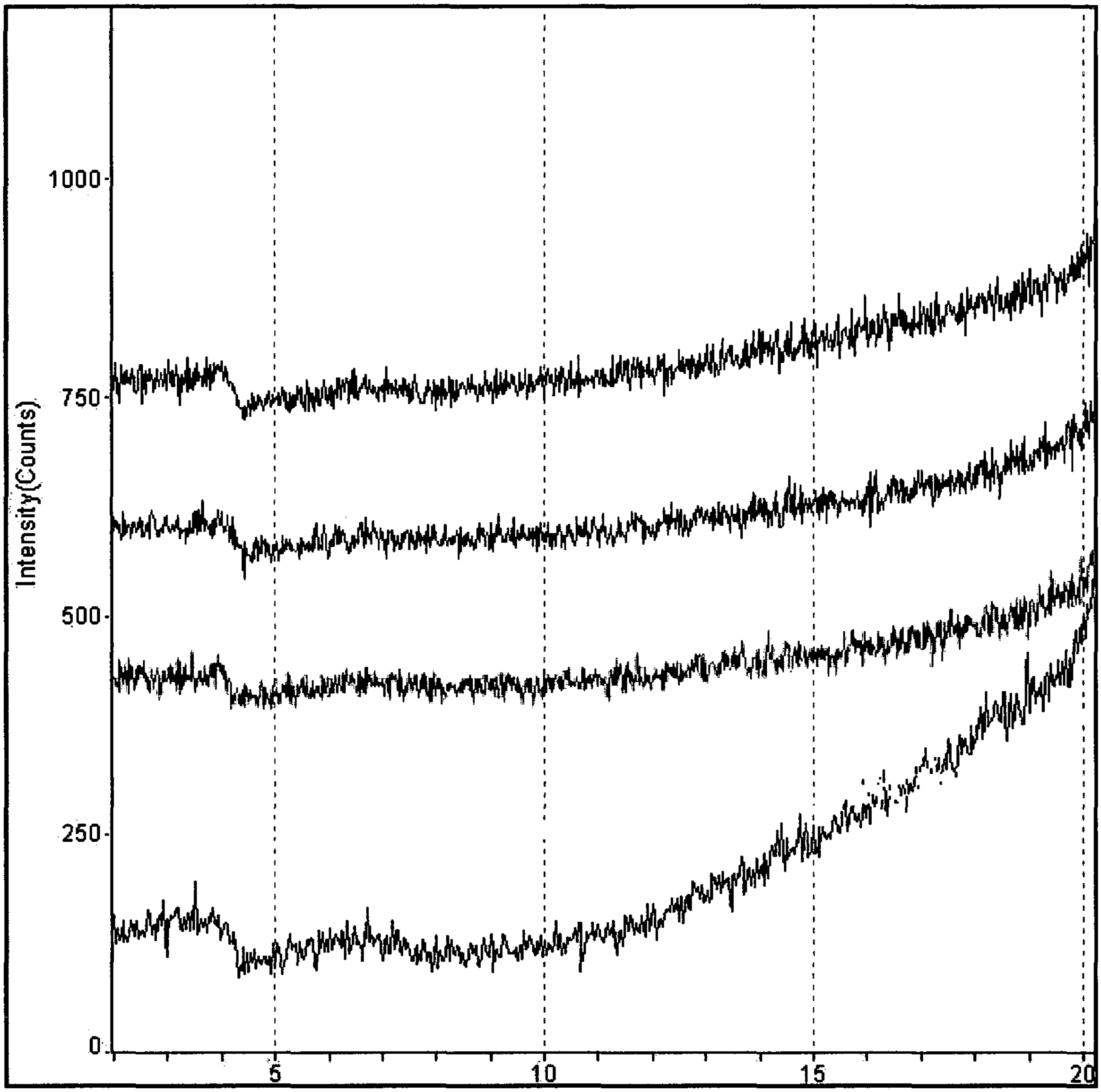
Lou_2L_100



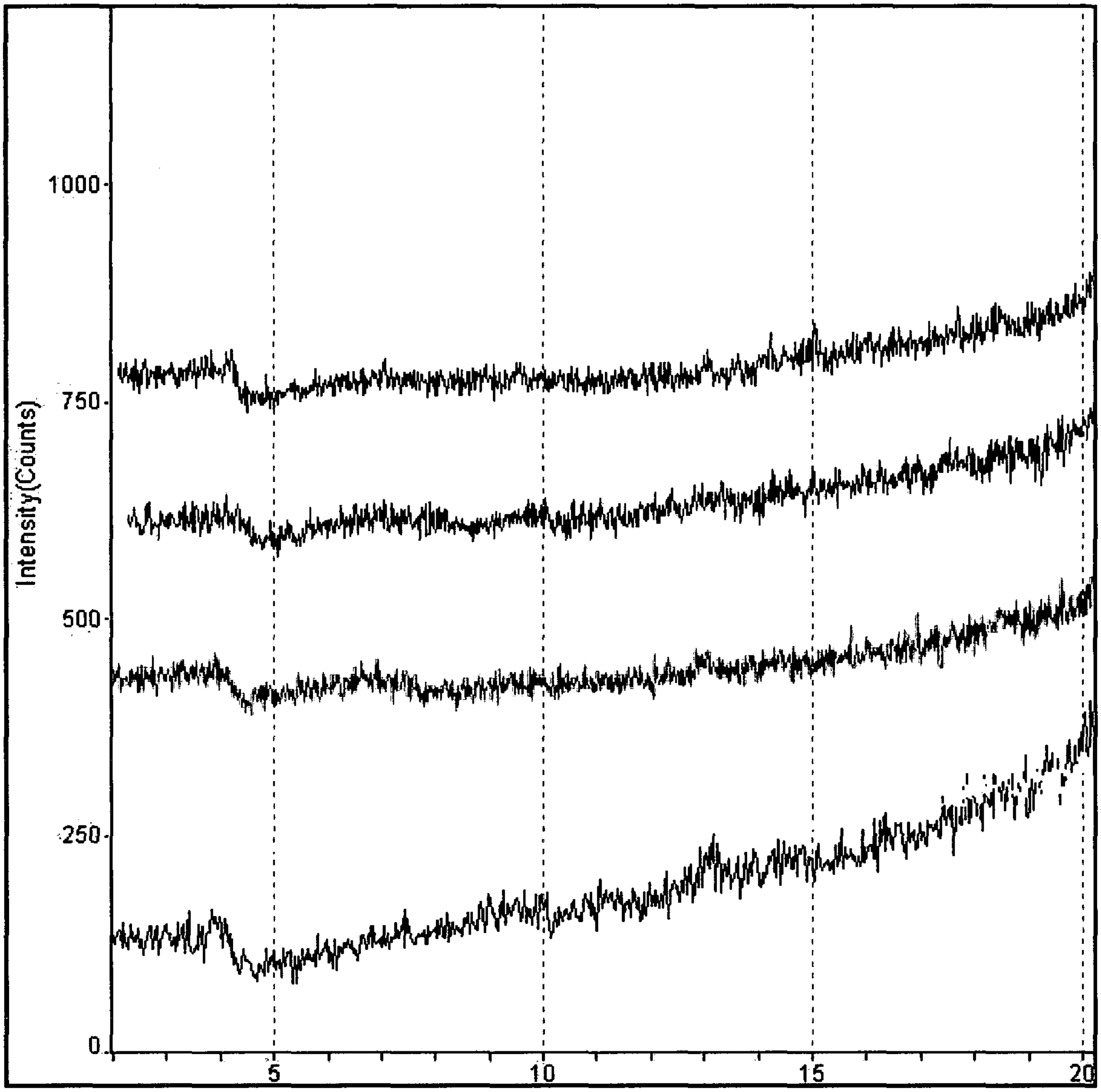
Lou_3L_10



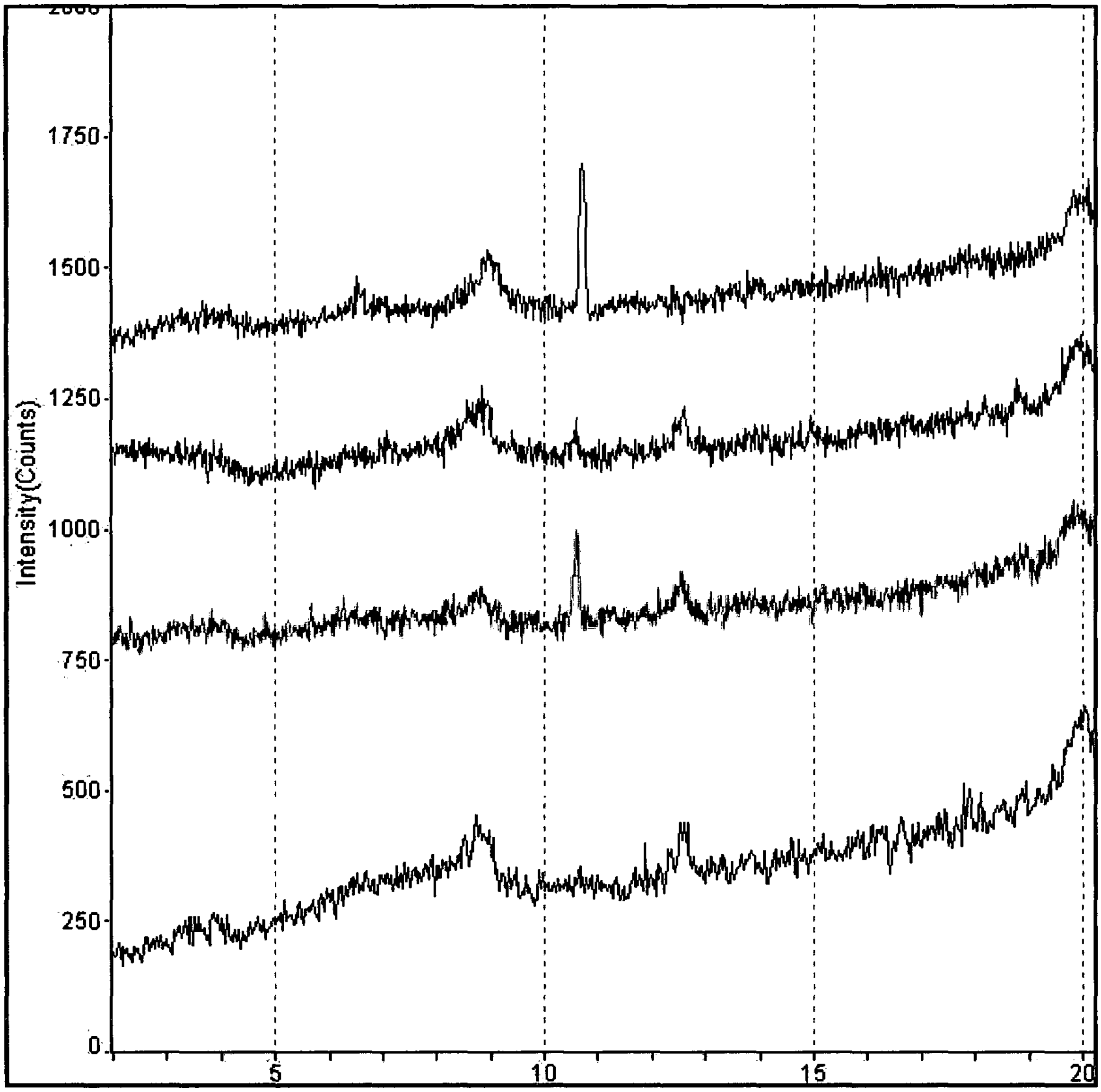
Lou_3L_20



Lou_3L_30



Lou_3L_40



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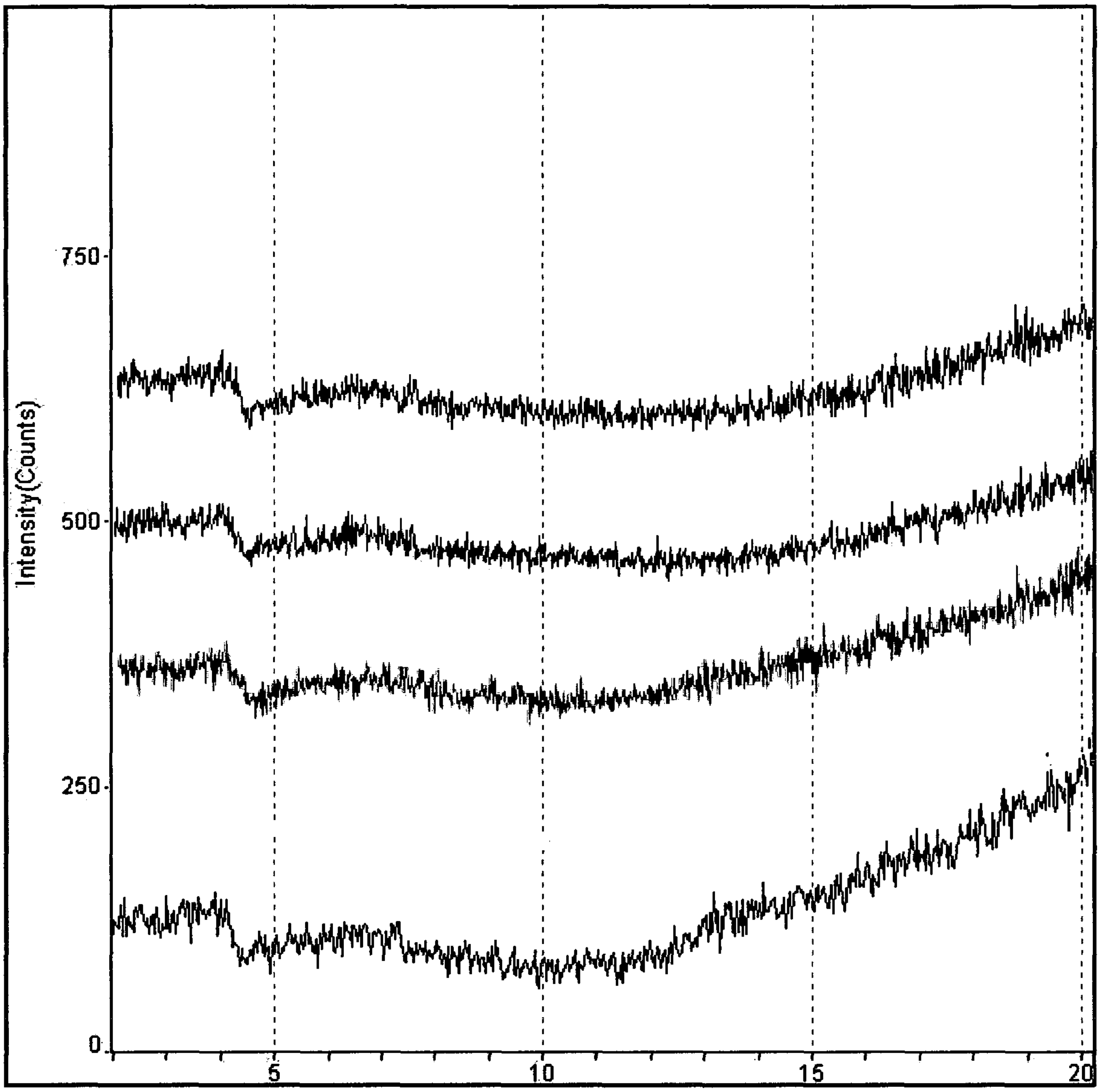
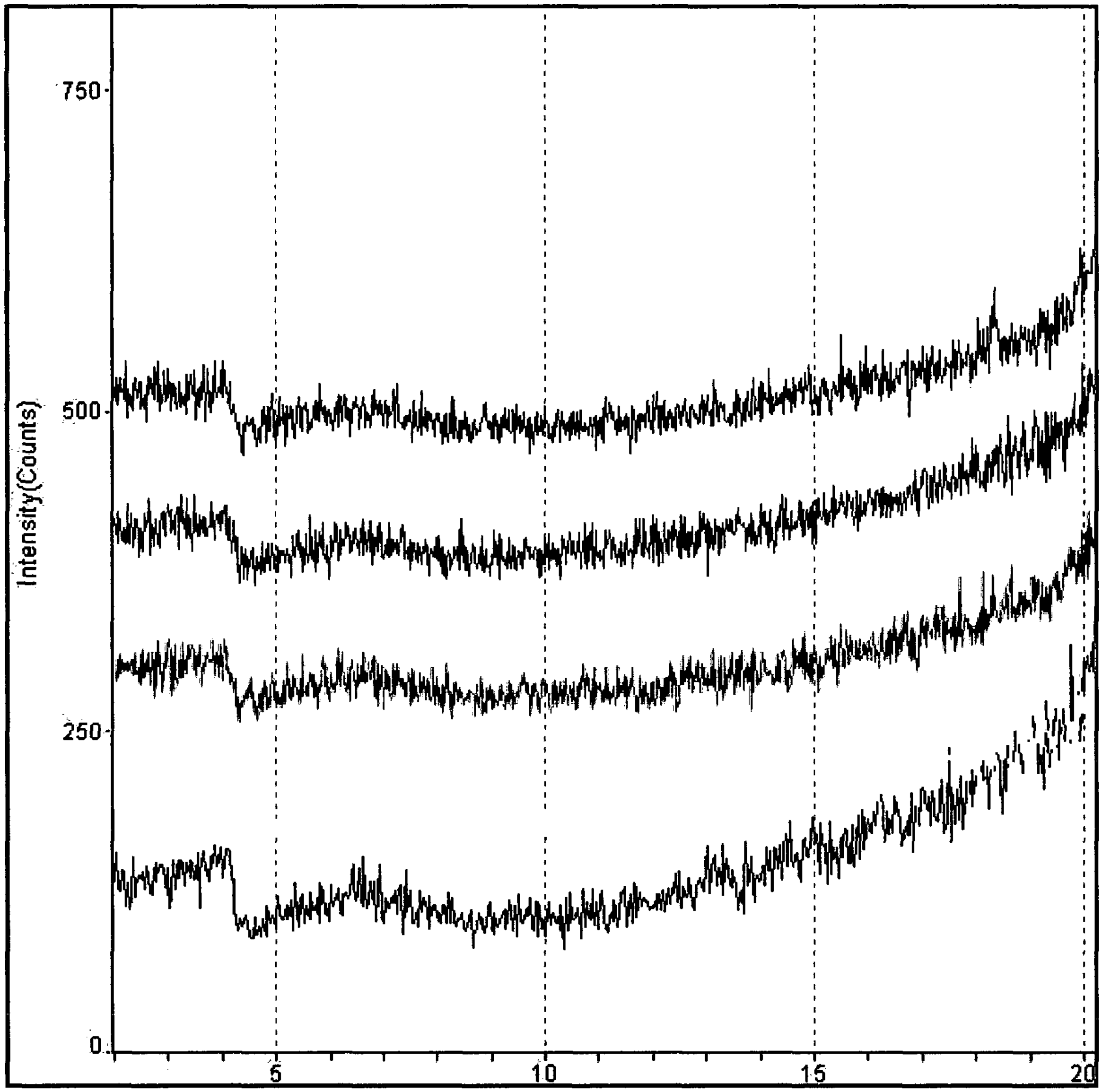
20

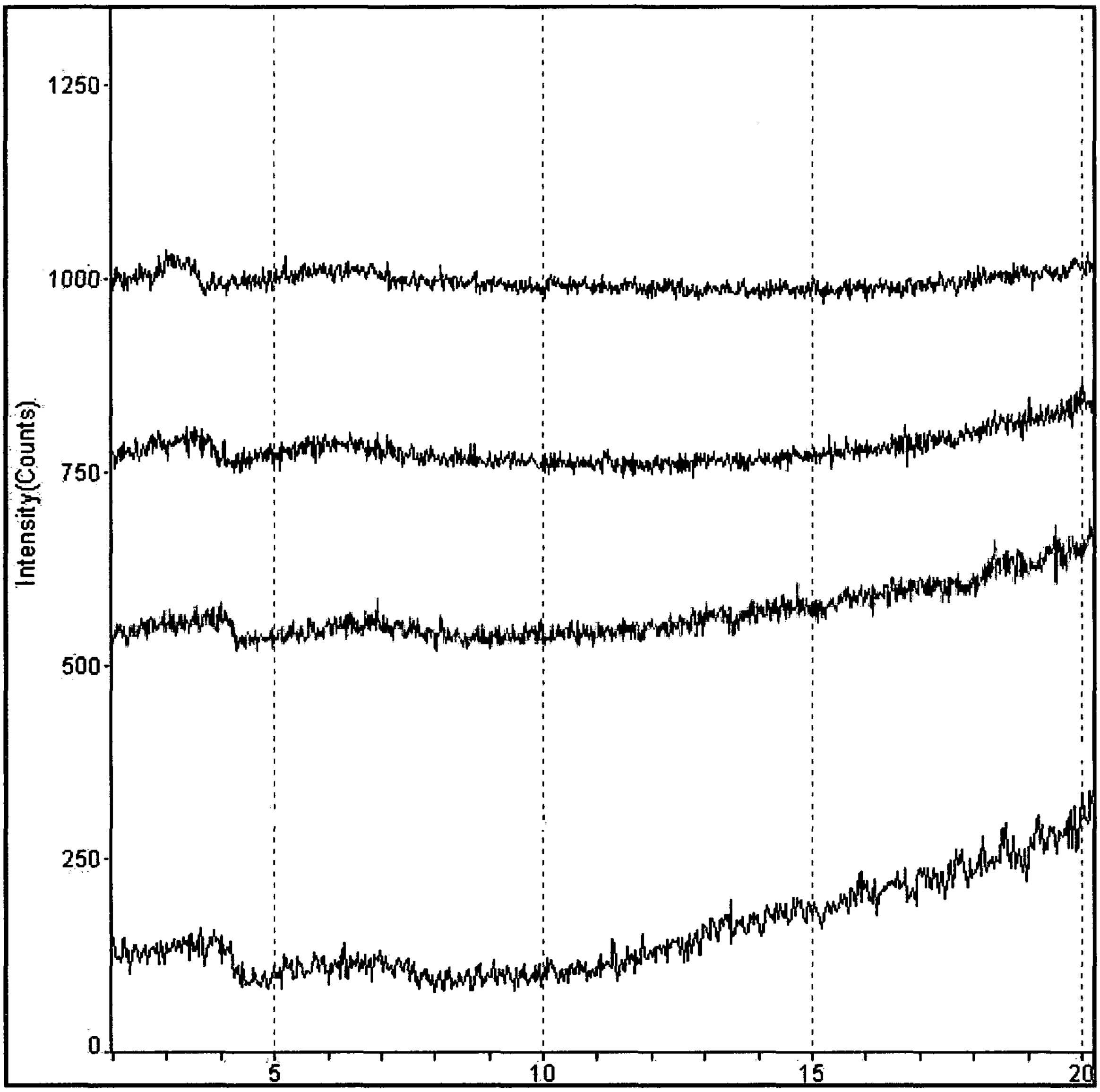
Lou_3L_50



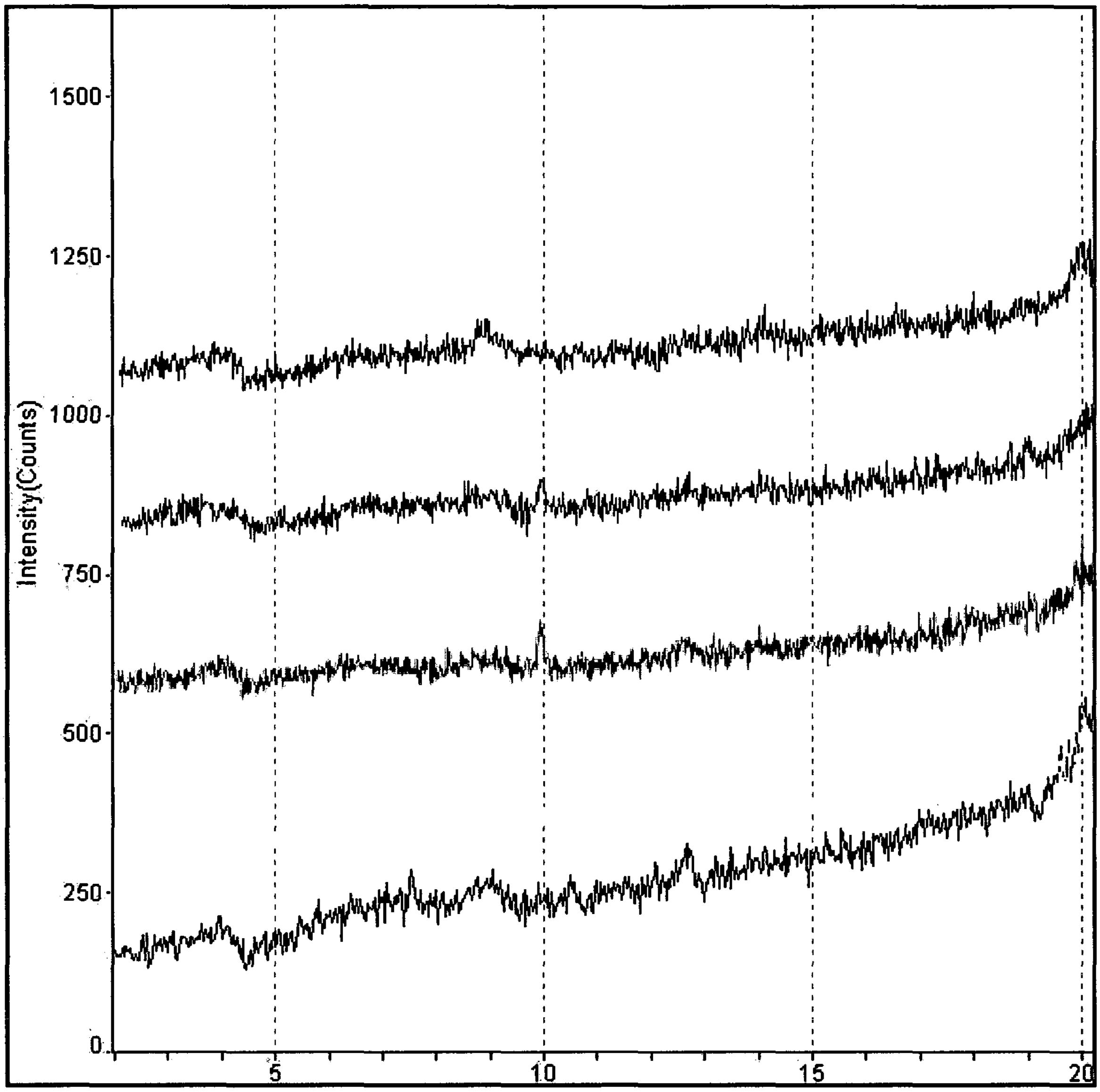
Lou_3L_60



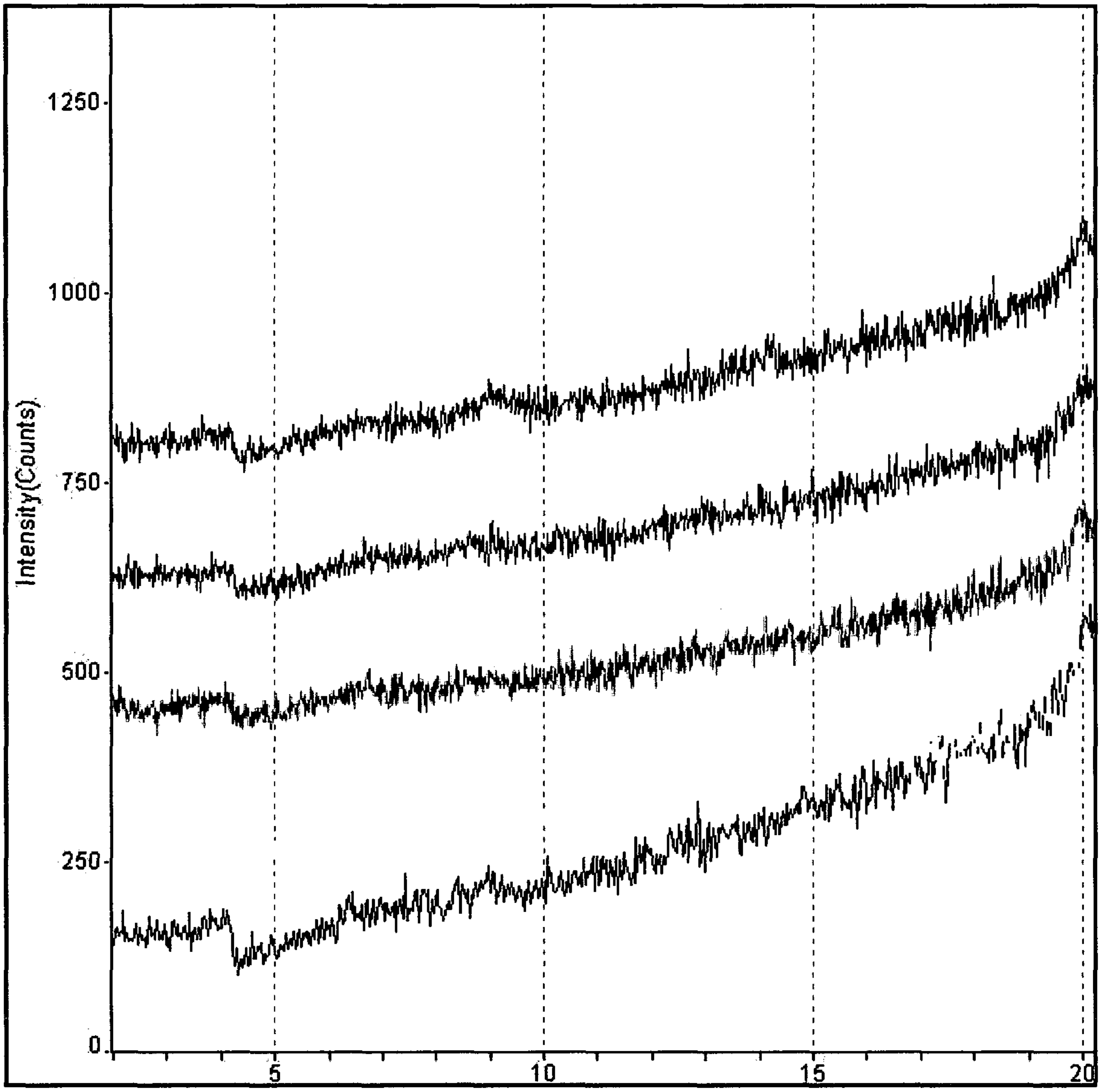
Lou_3L_70



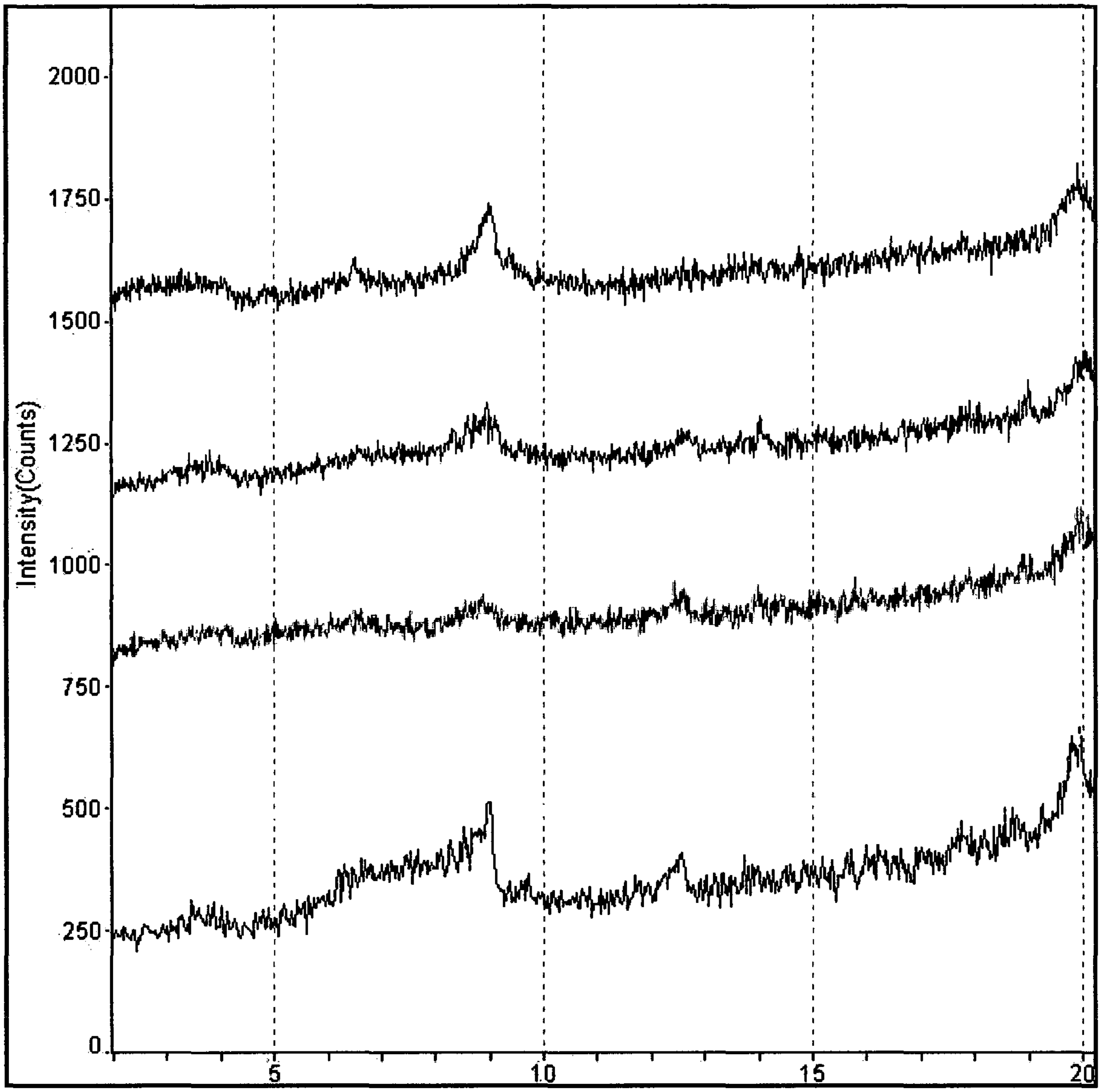
Lou_3L_80



Lou_4L_02



Lou_4L_12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Intensity(Counts)
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15
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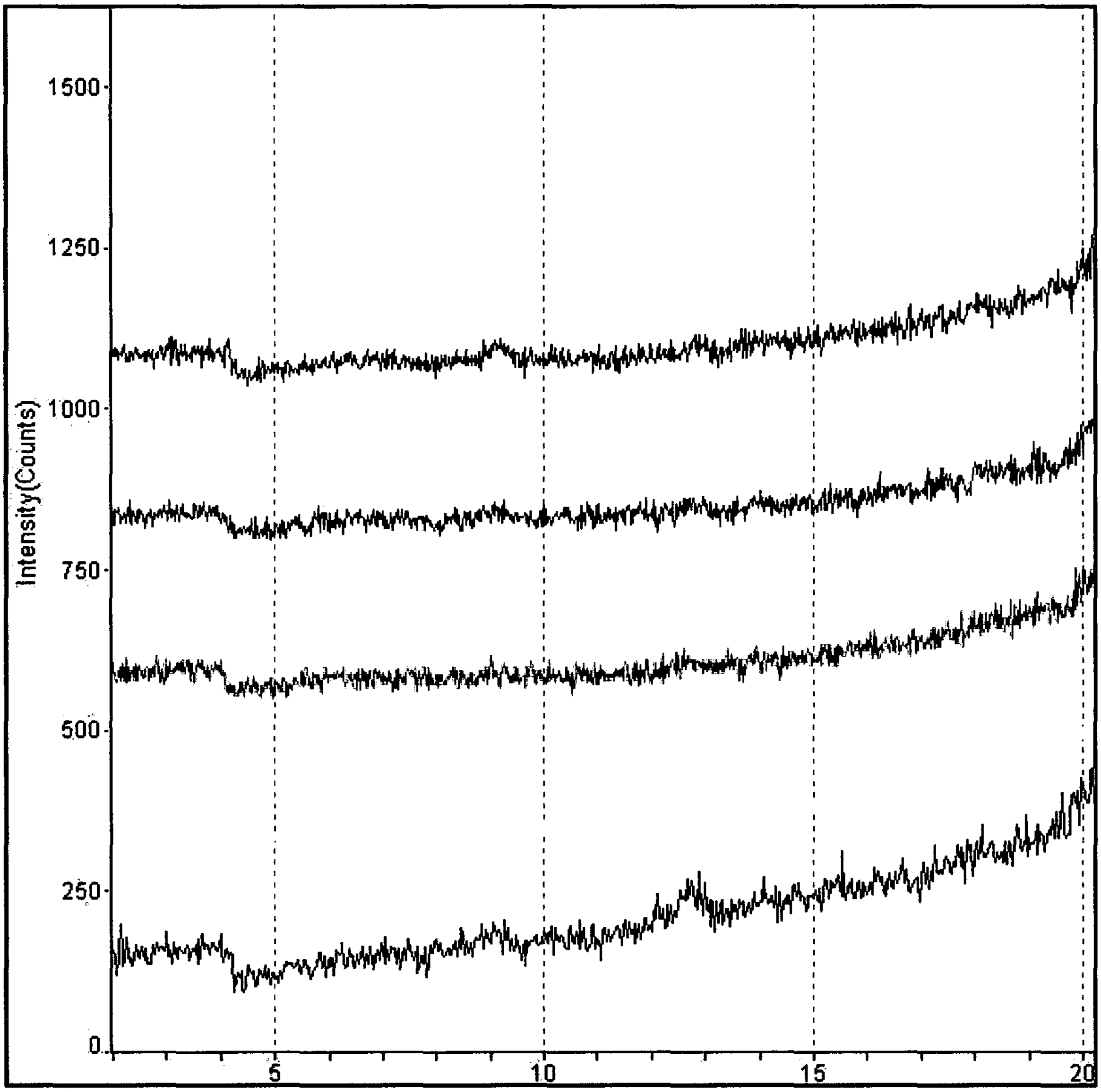
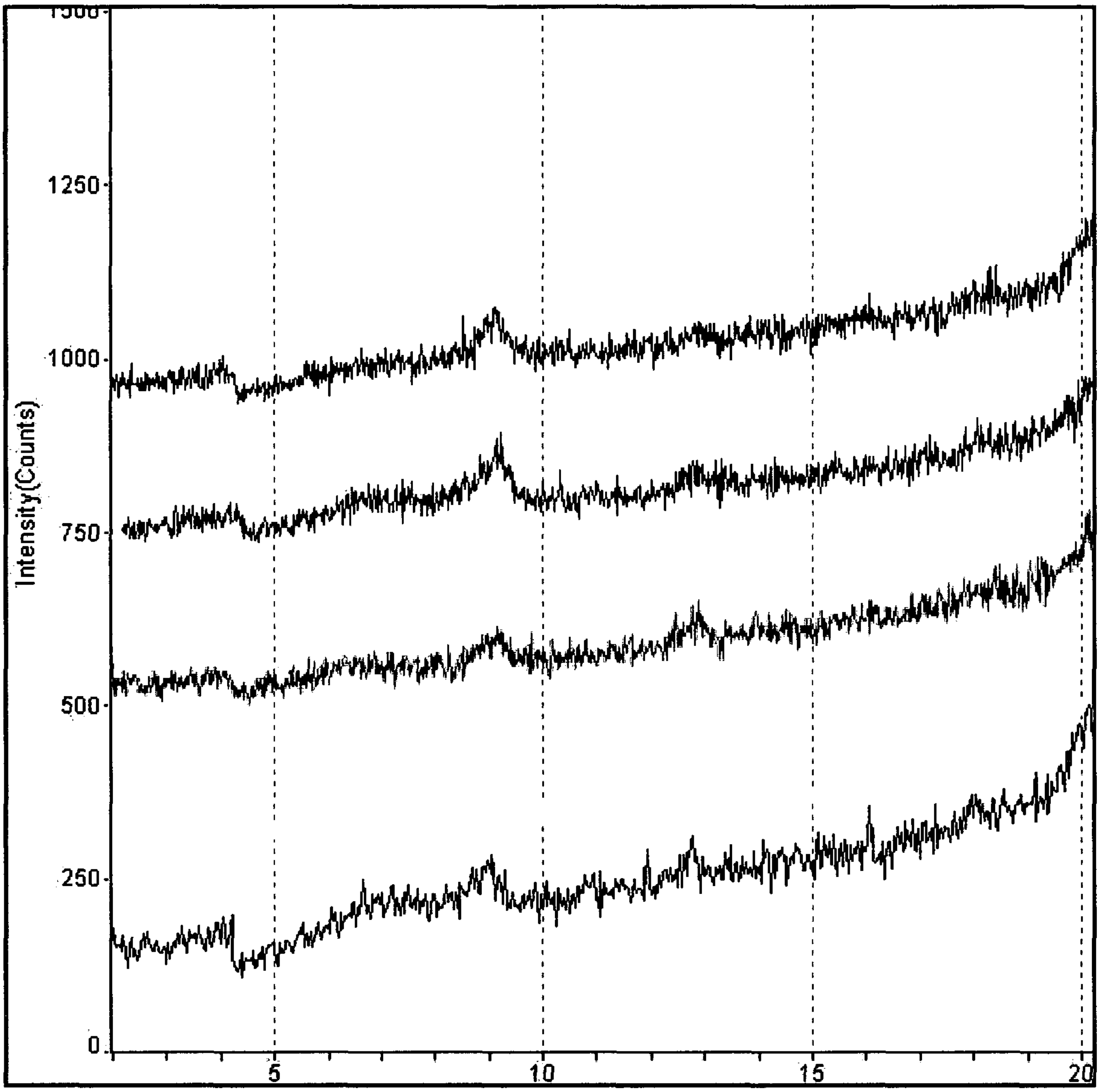
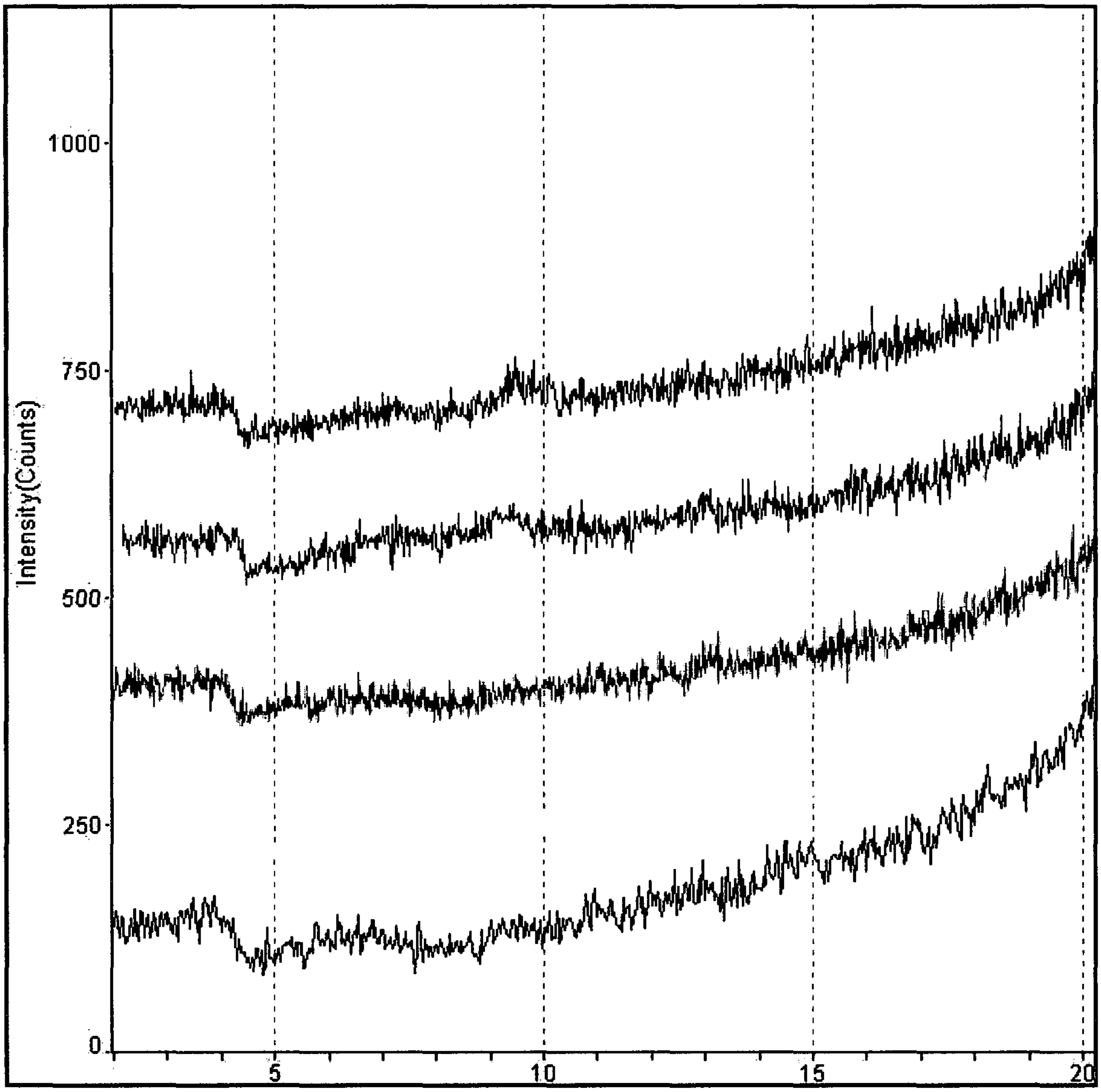
Lou_4L_22



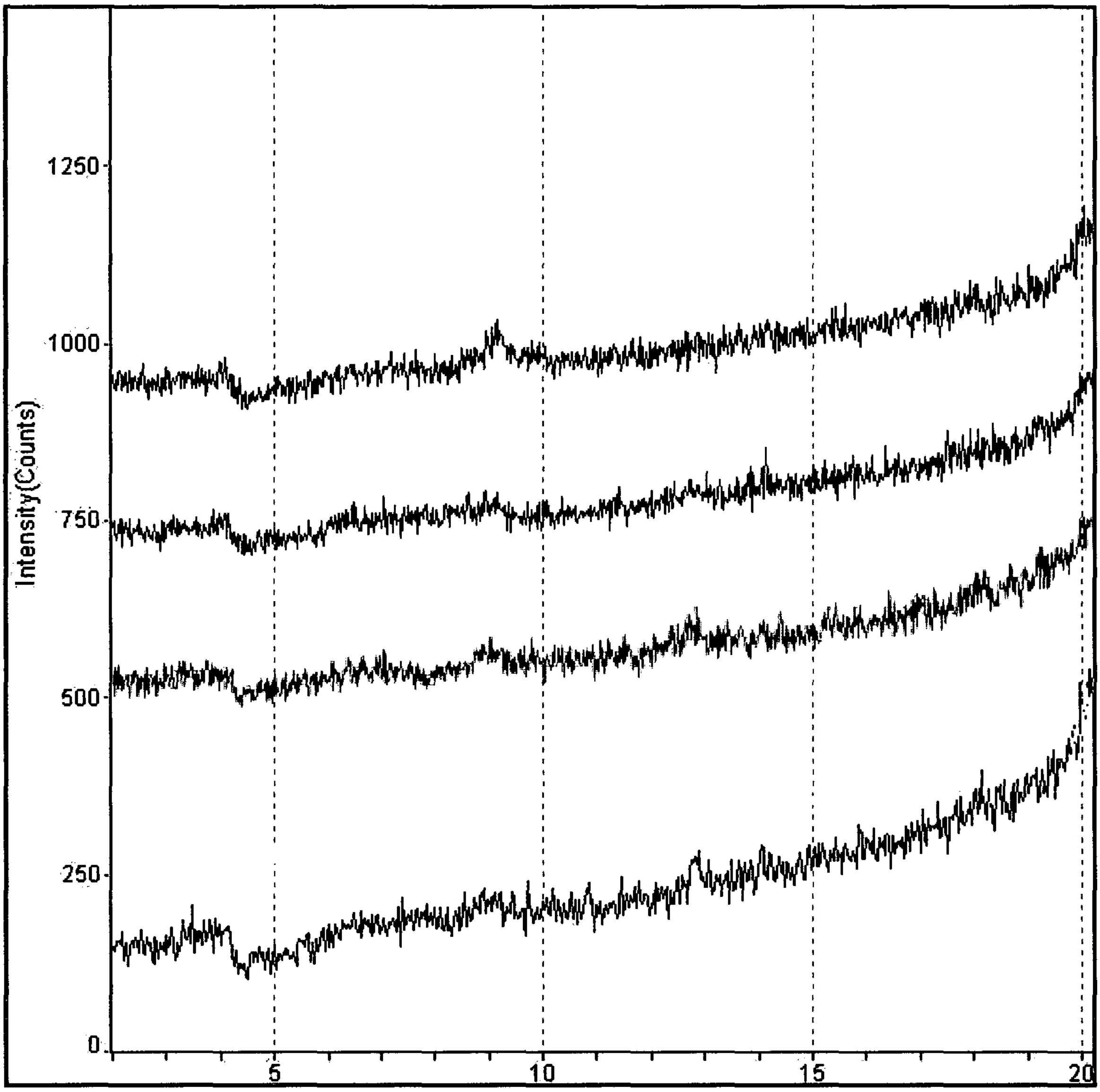
Lou_4L_32



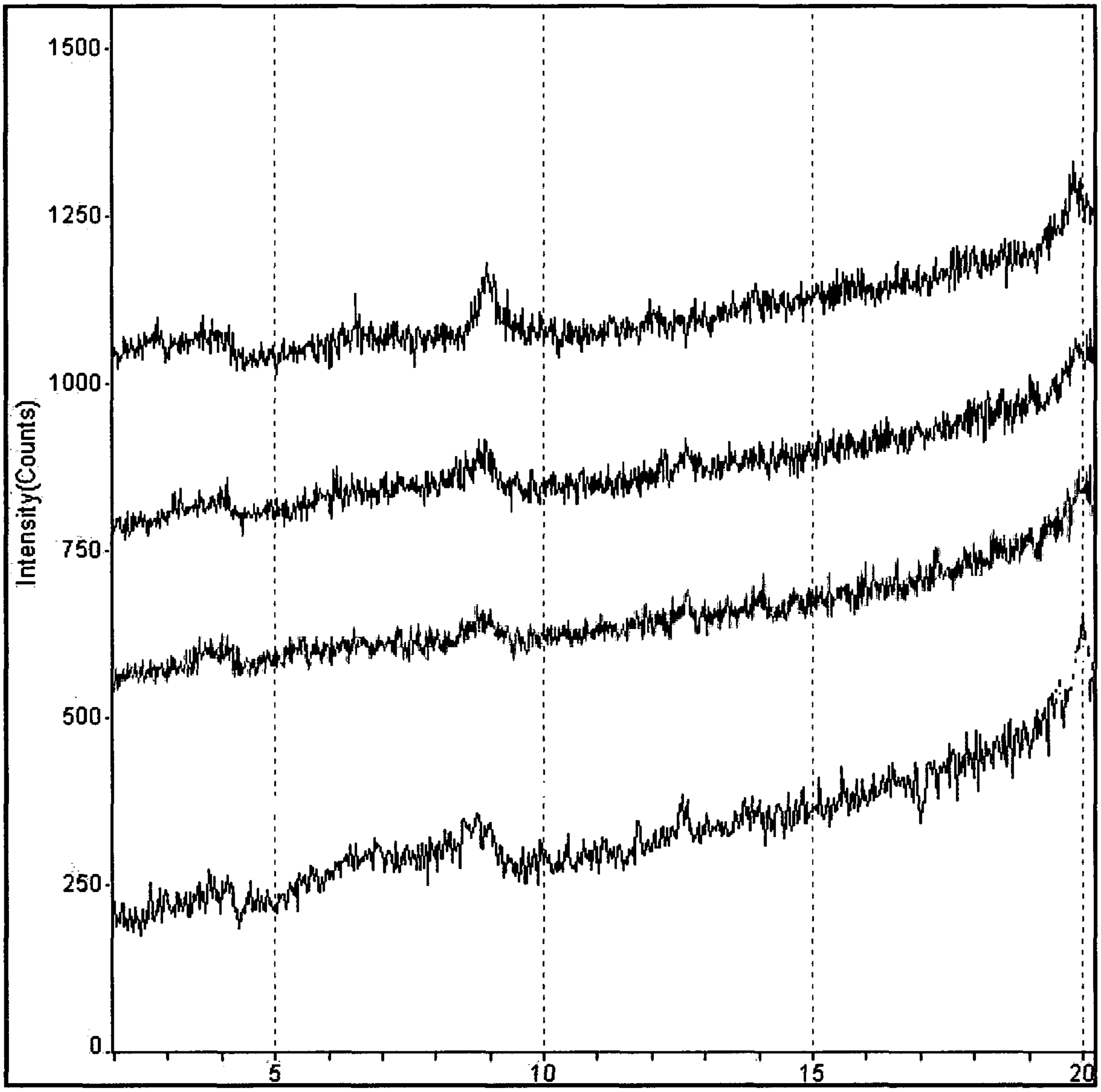
Lou_4L_42



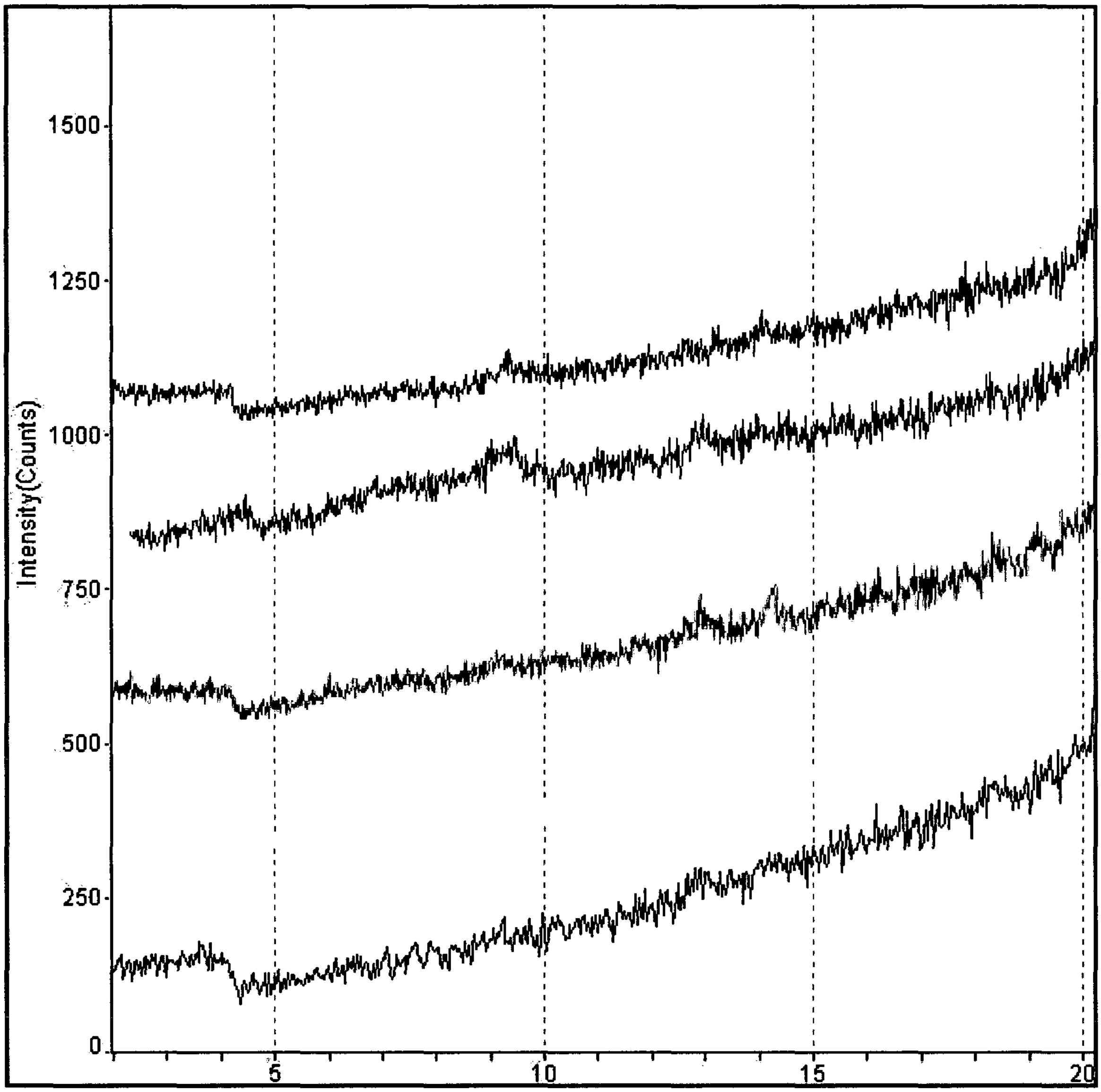
Lou_4L_52



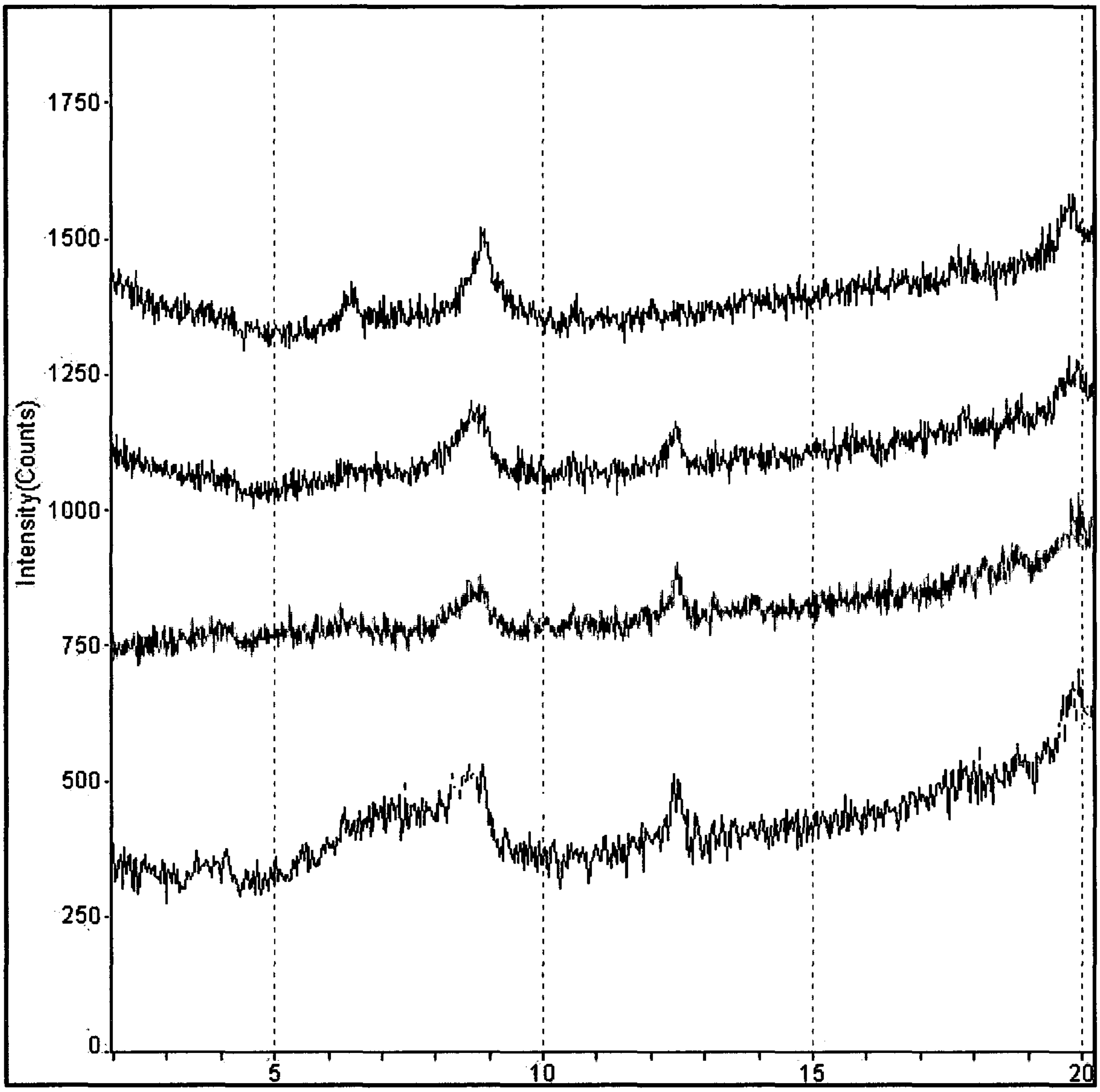
Lou_4L_62



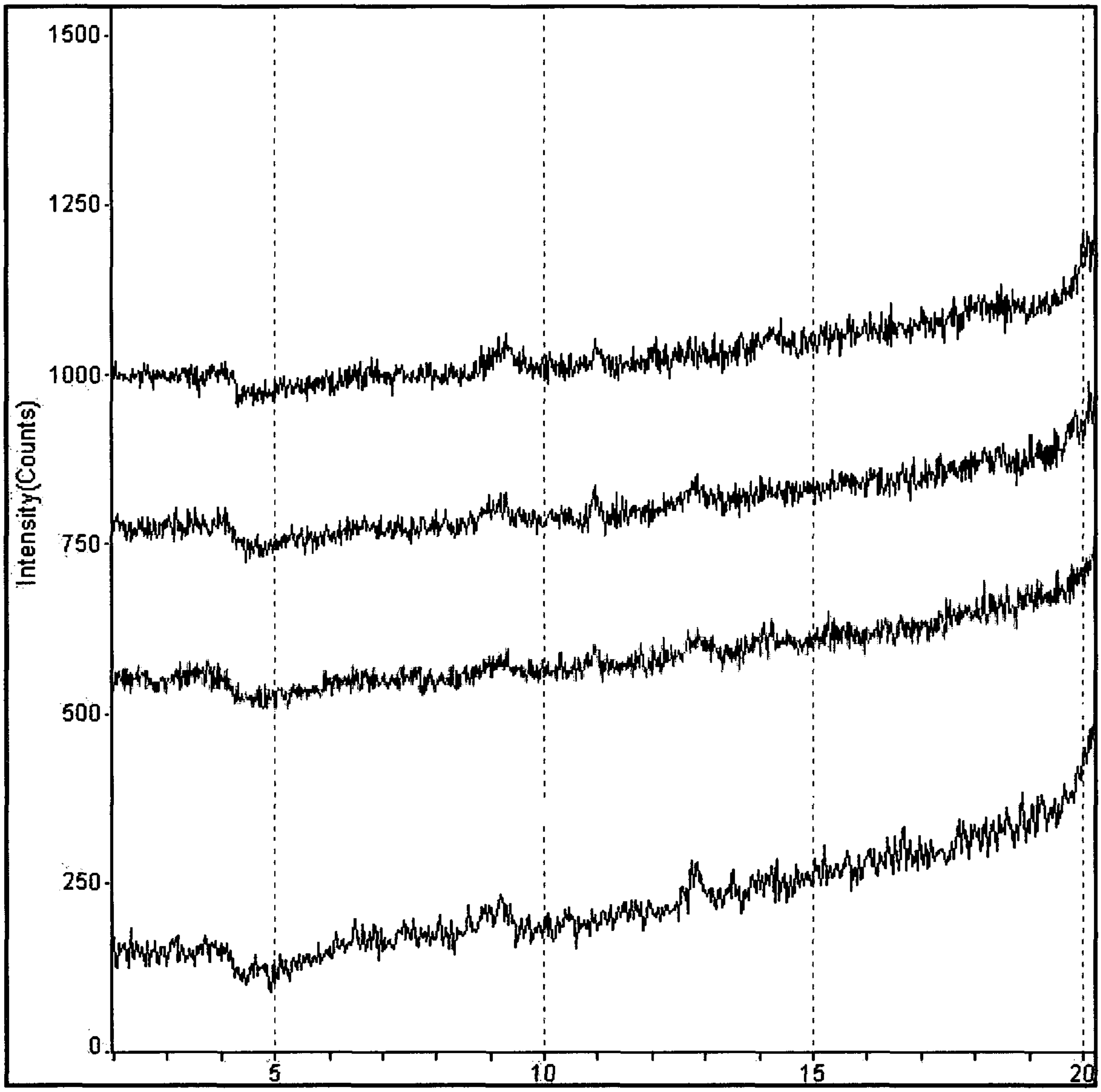
Lou_4L_72



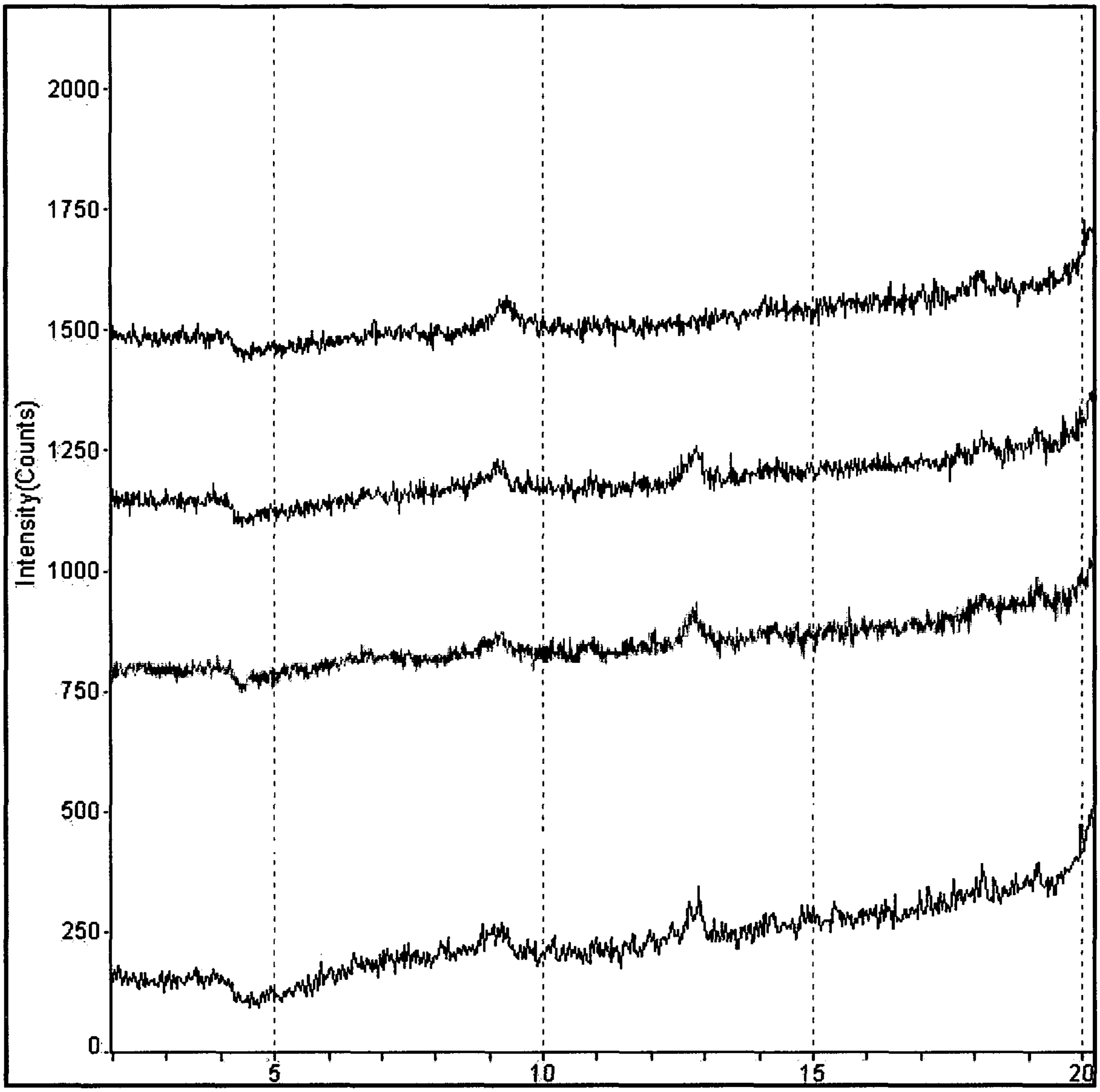
Lou_4L_82



Lou_4L_92



Lou_4L_102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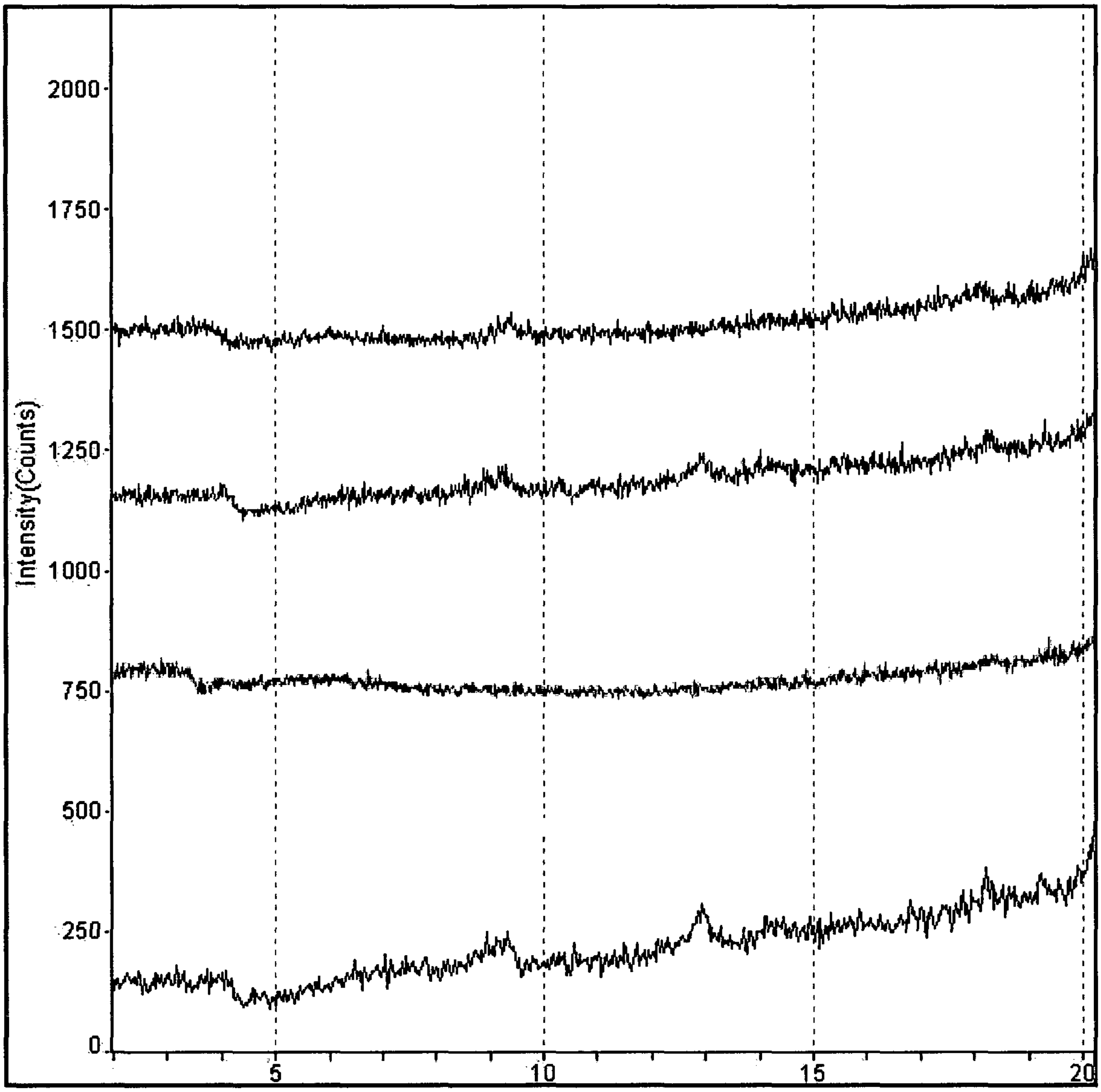
20

Lou_5L_11


Intensity(Counts)
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15
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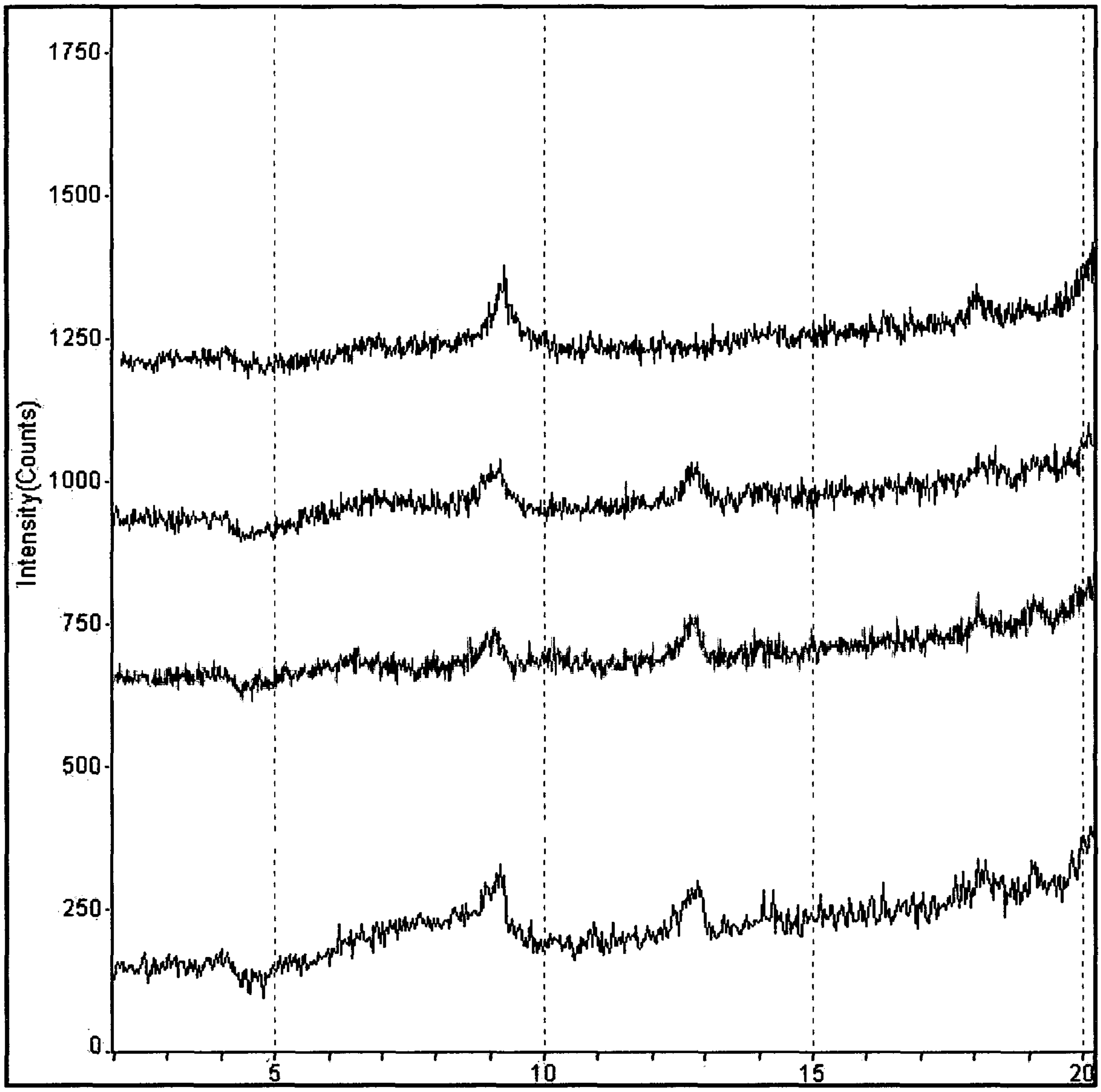
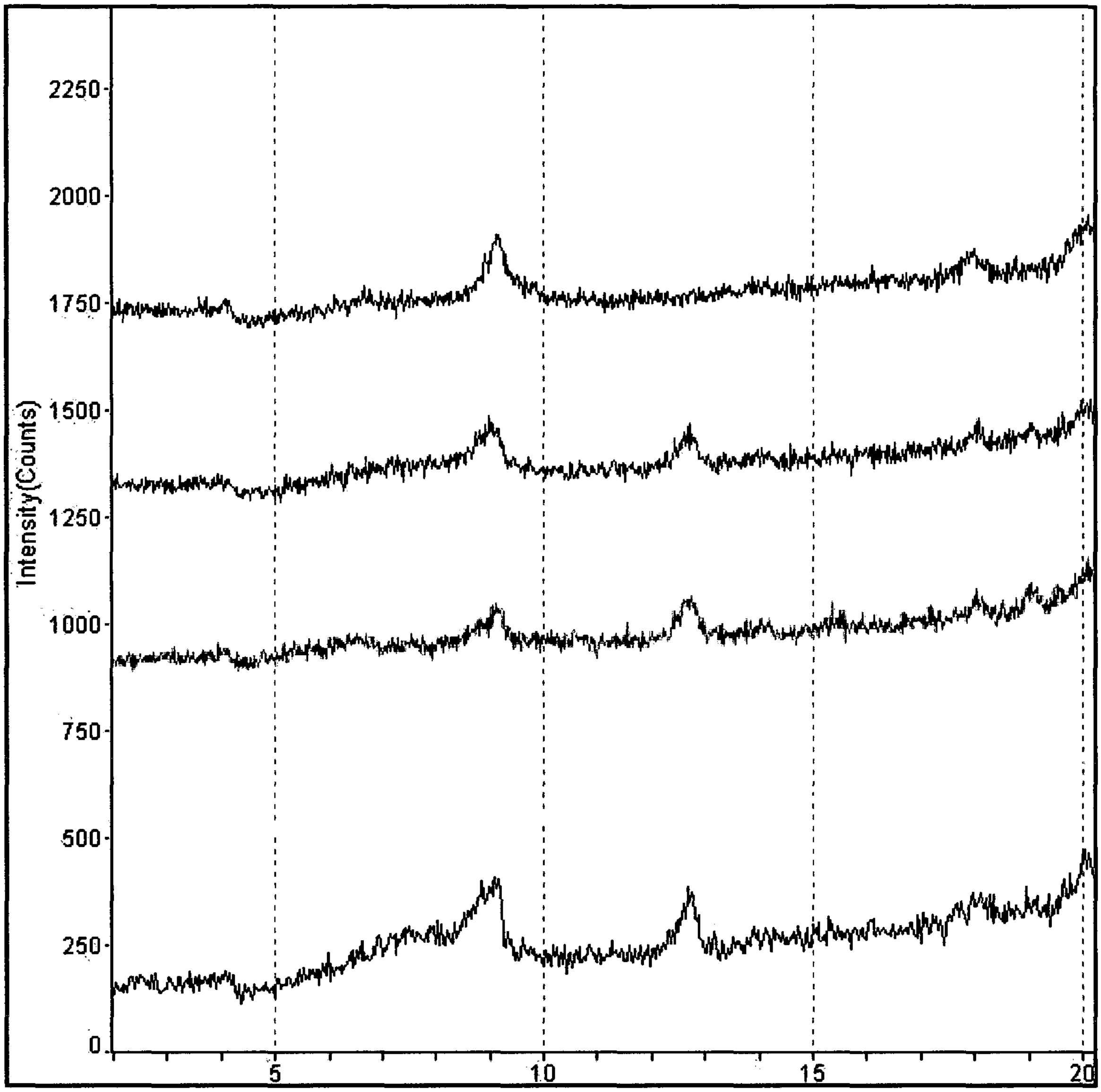
Lou_5L_21



Lou_5L_31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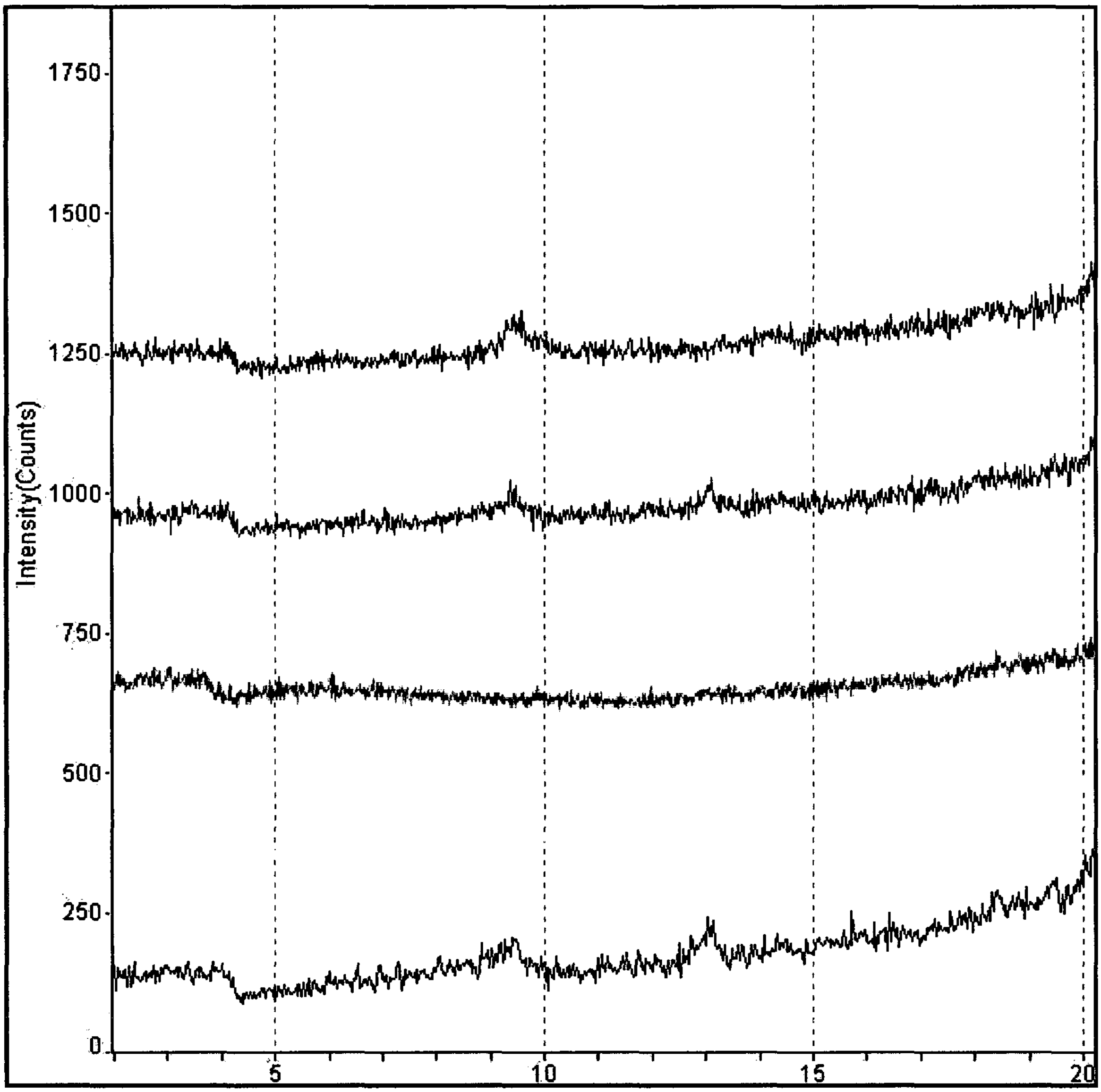
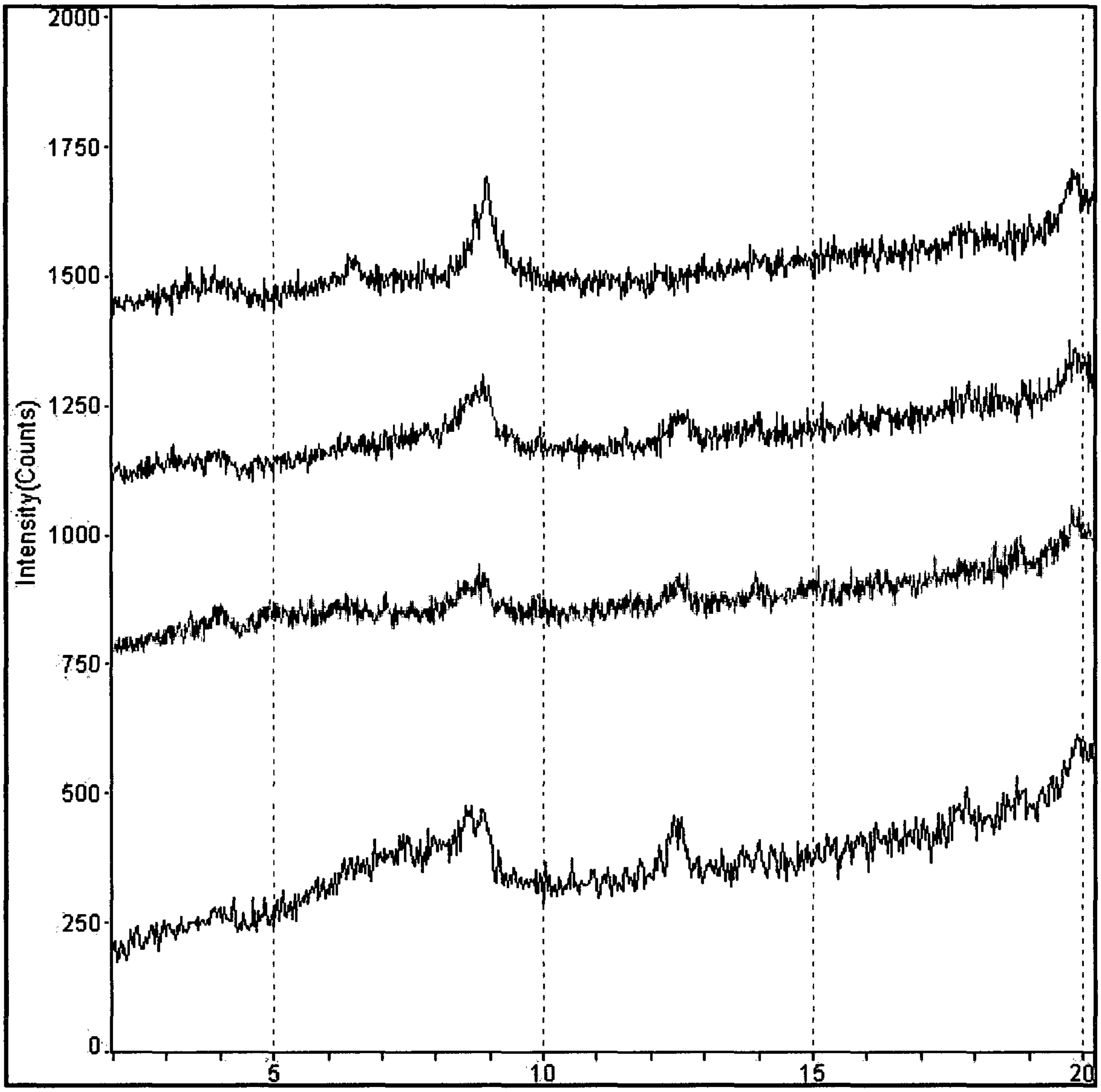
Lou_5L_41



Lou_5L_51



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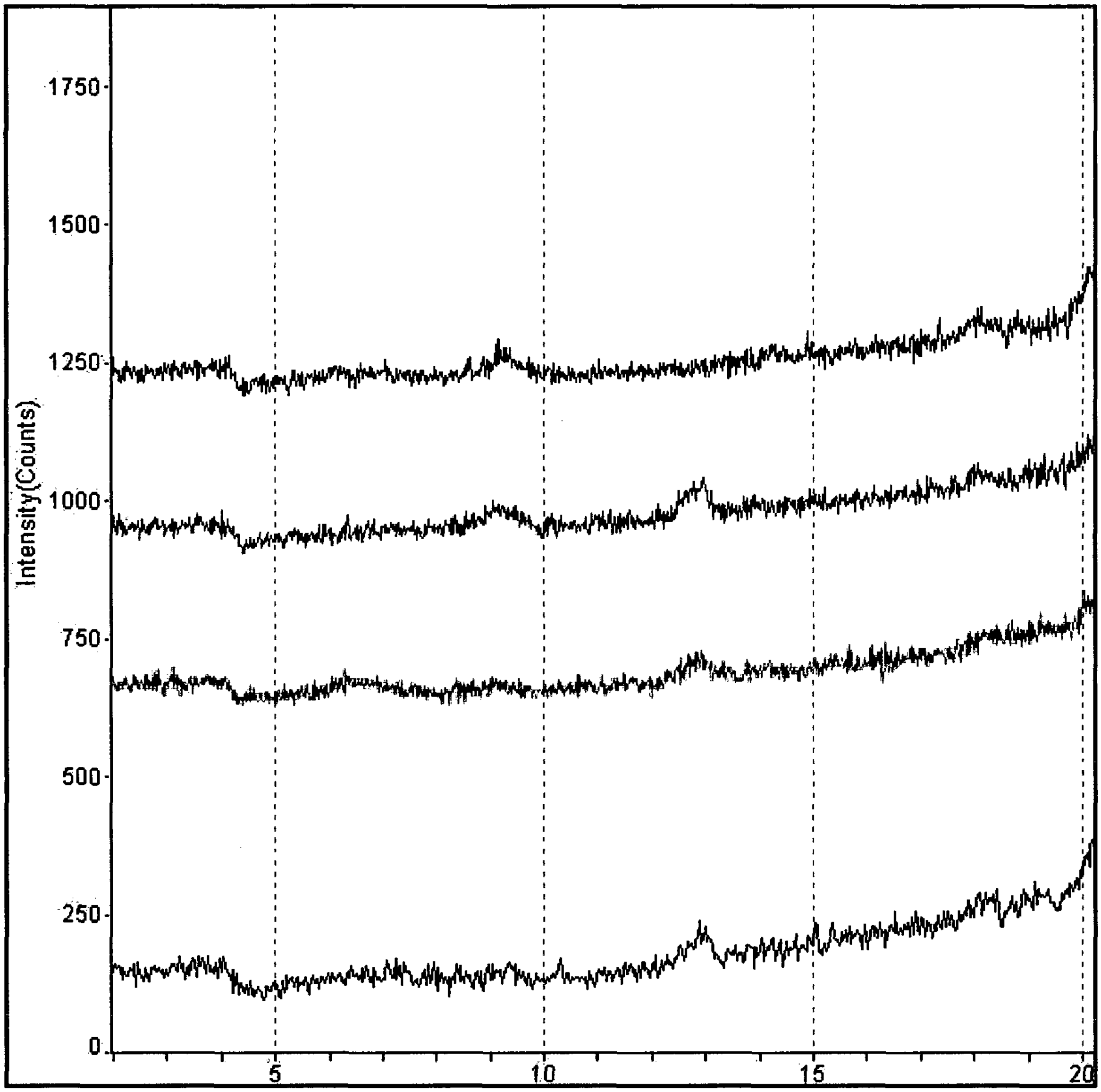
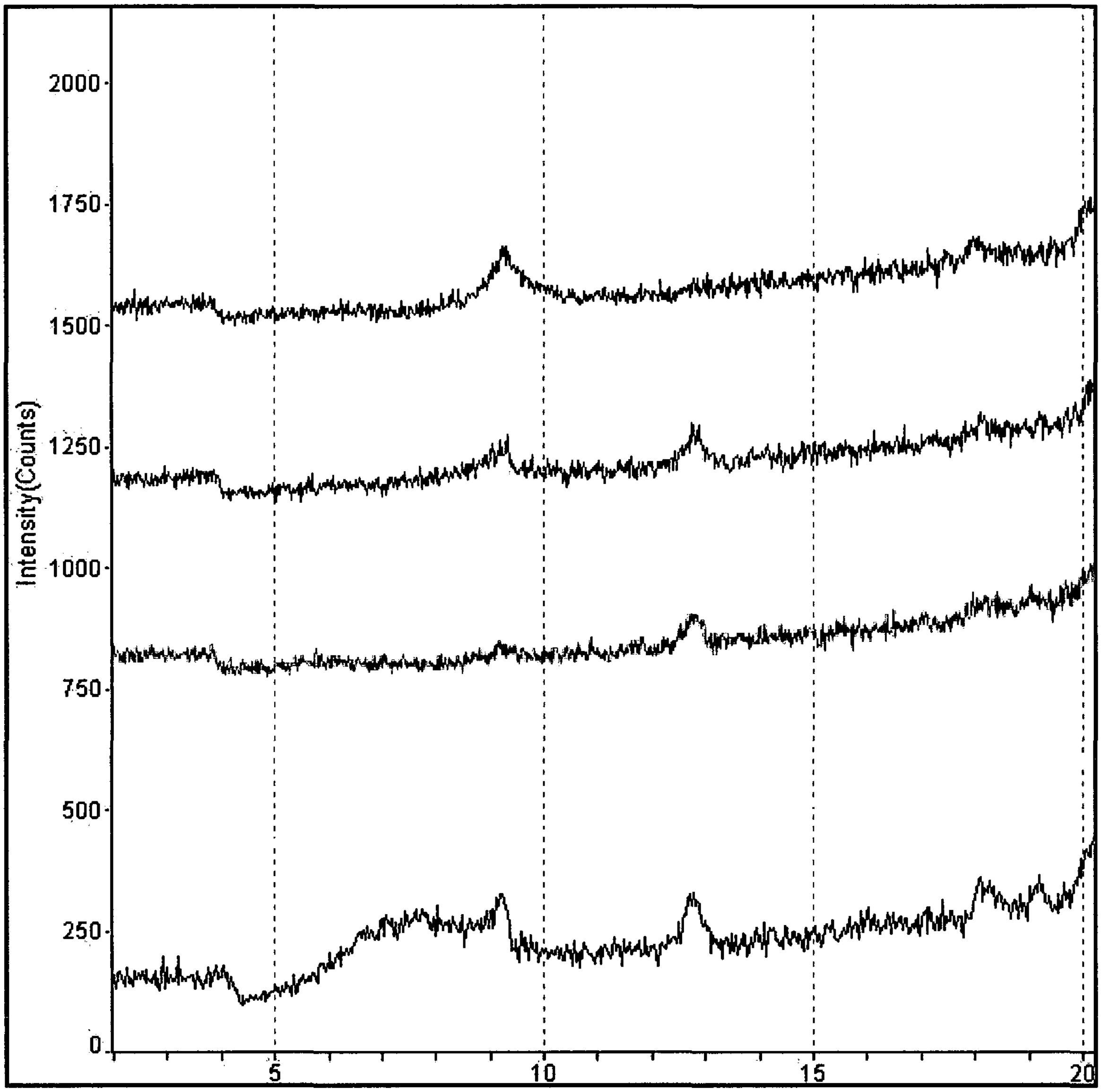
Lou_5L_61



Lou_5L_71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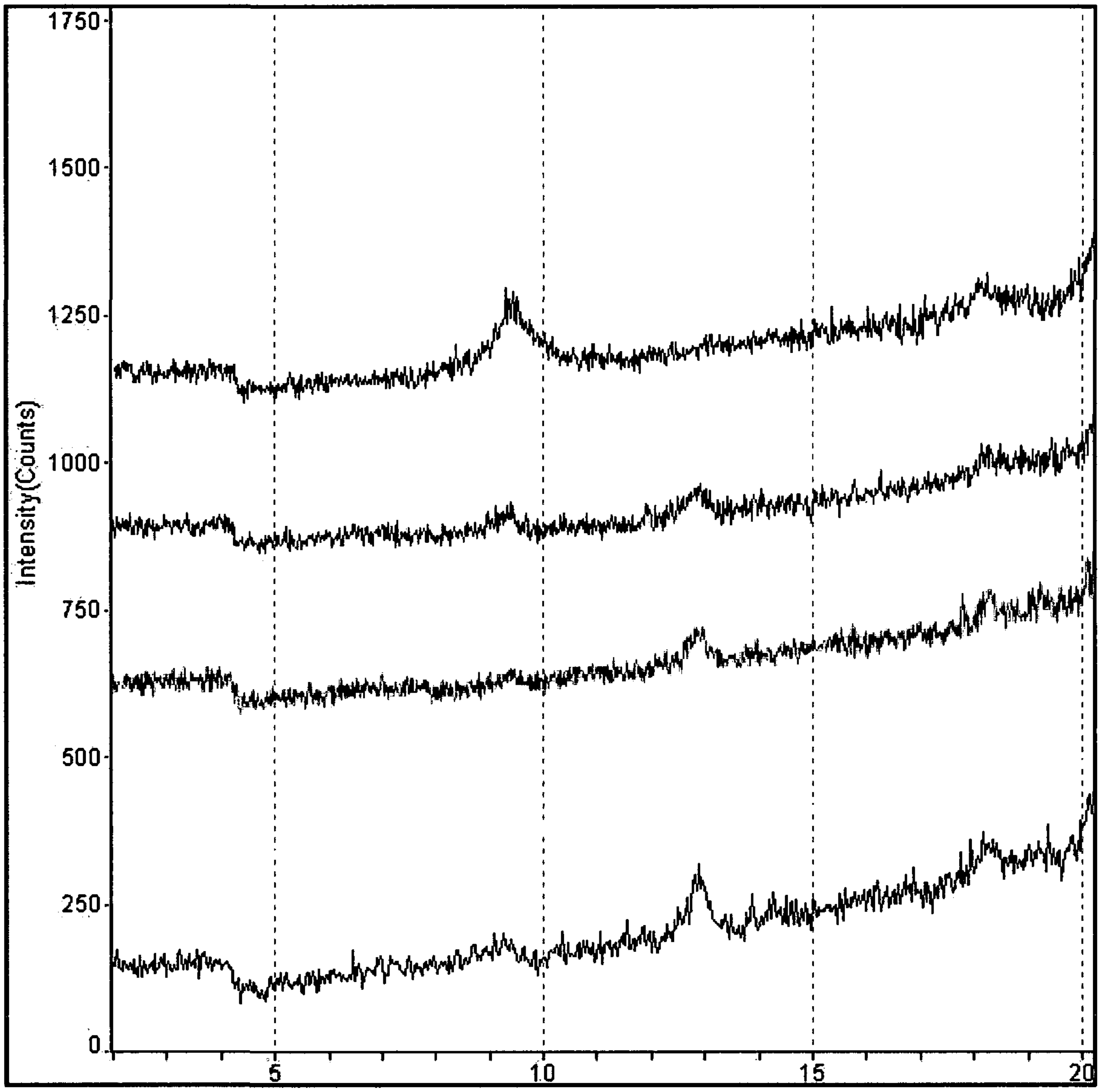
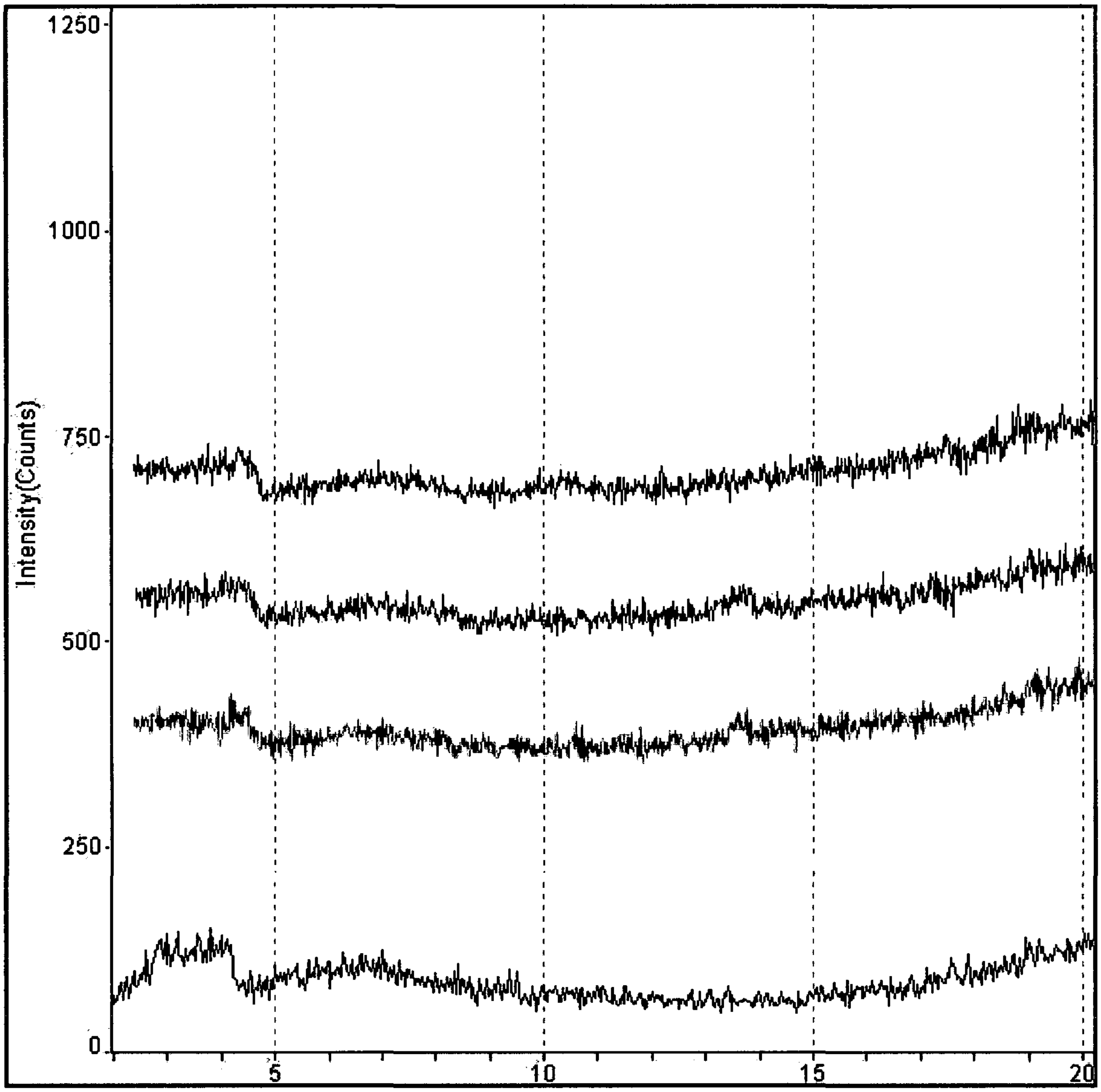
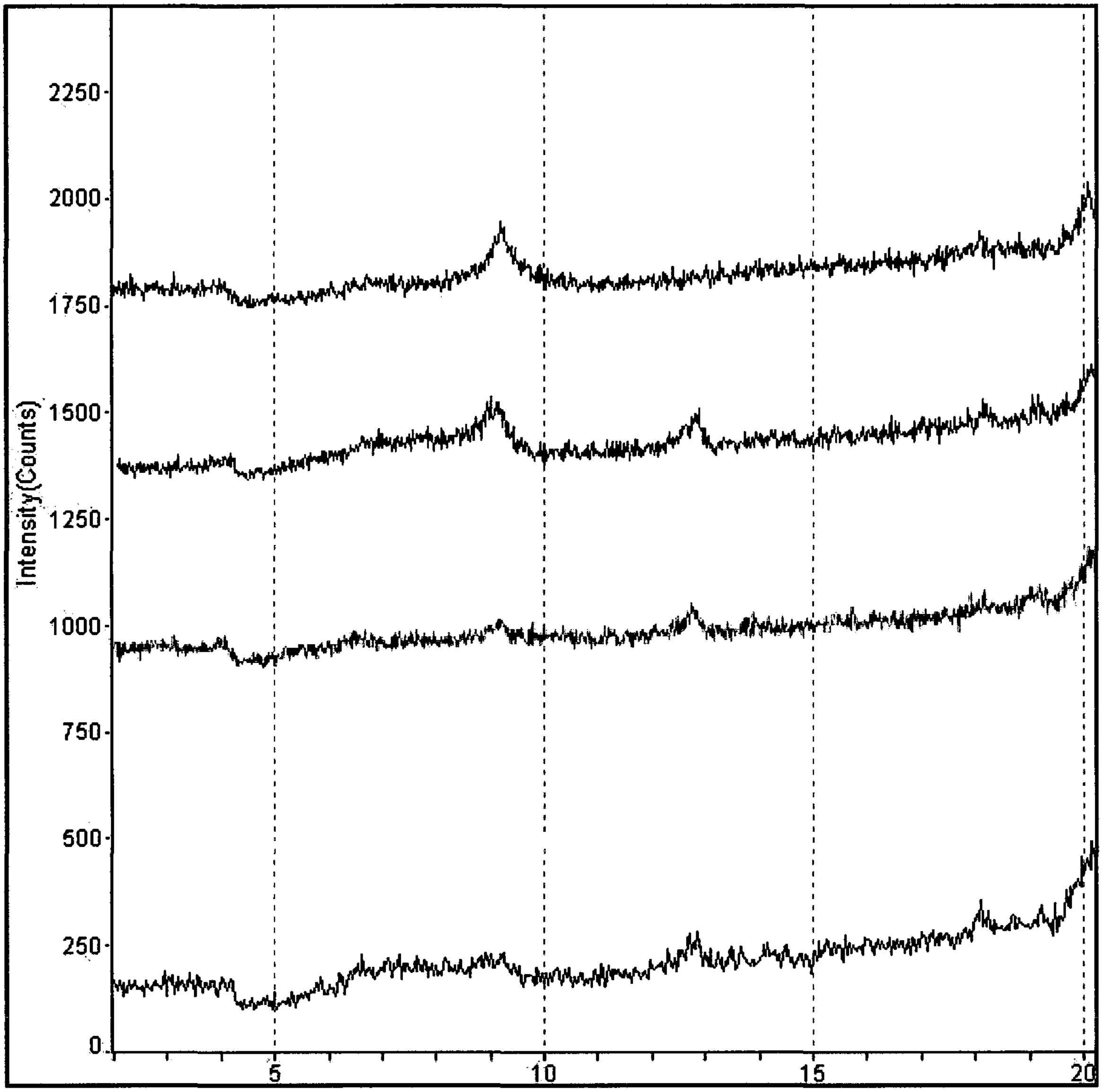
Lou_5L_81



Lou_5L_91



Lou_6L_09



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Intensity(Counts)
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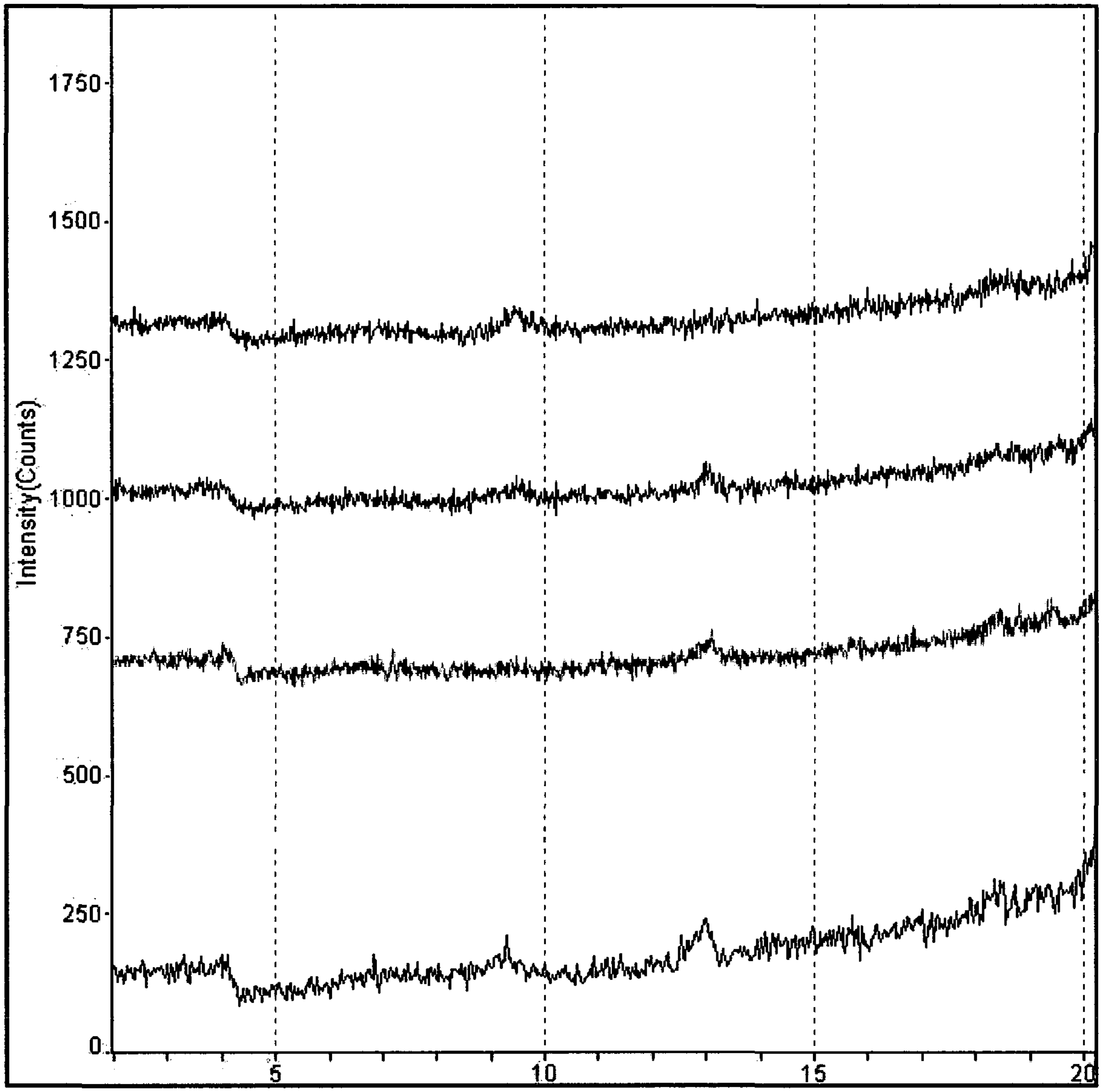
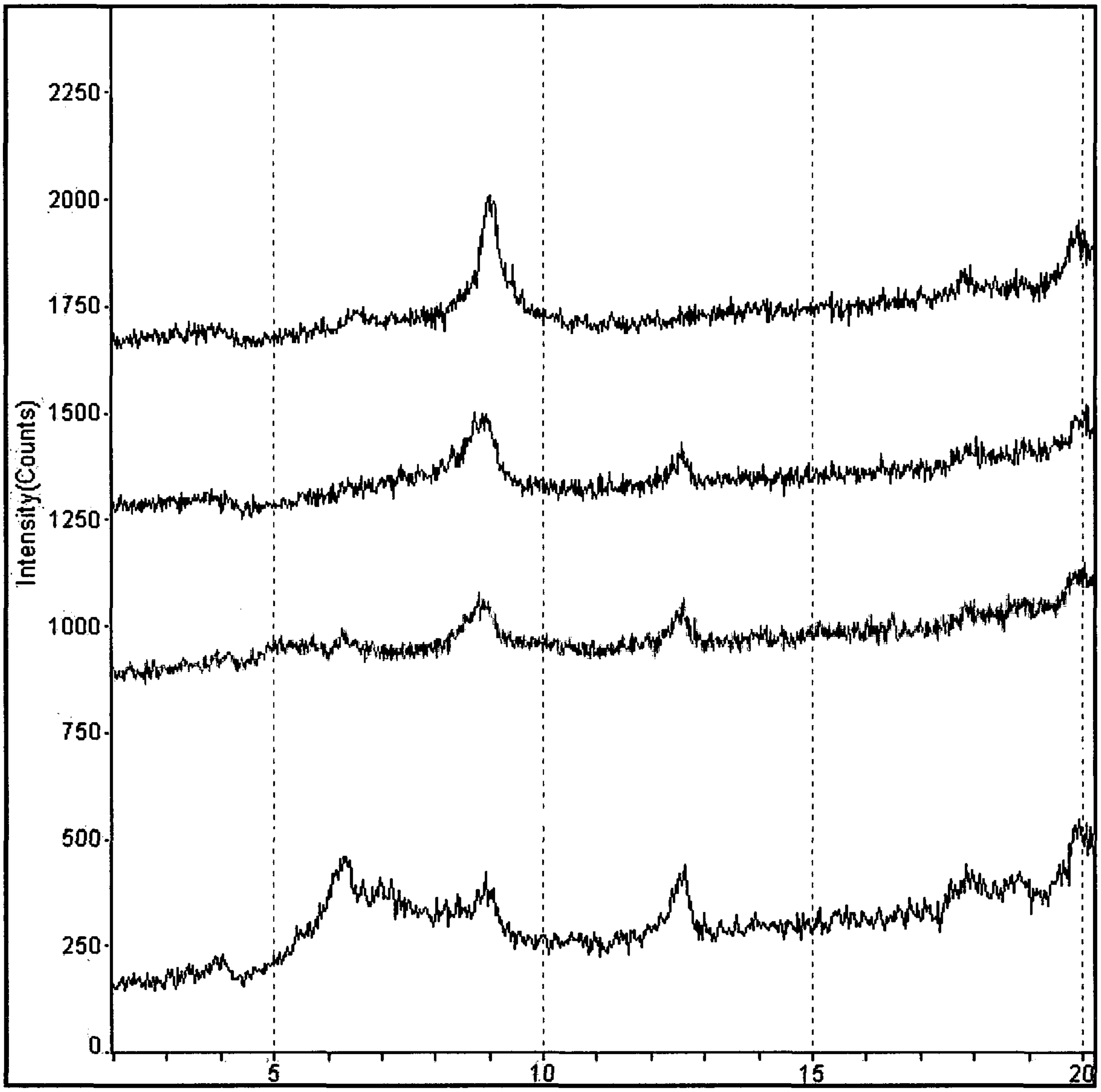
10
15
20

Lou_6L_29



Lou_6L_49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Intensity(Counts)
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15
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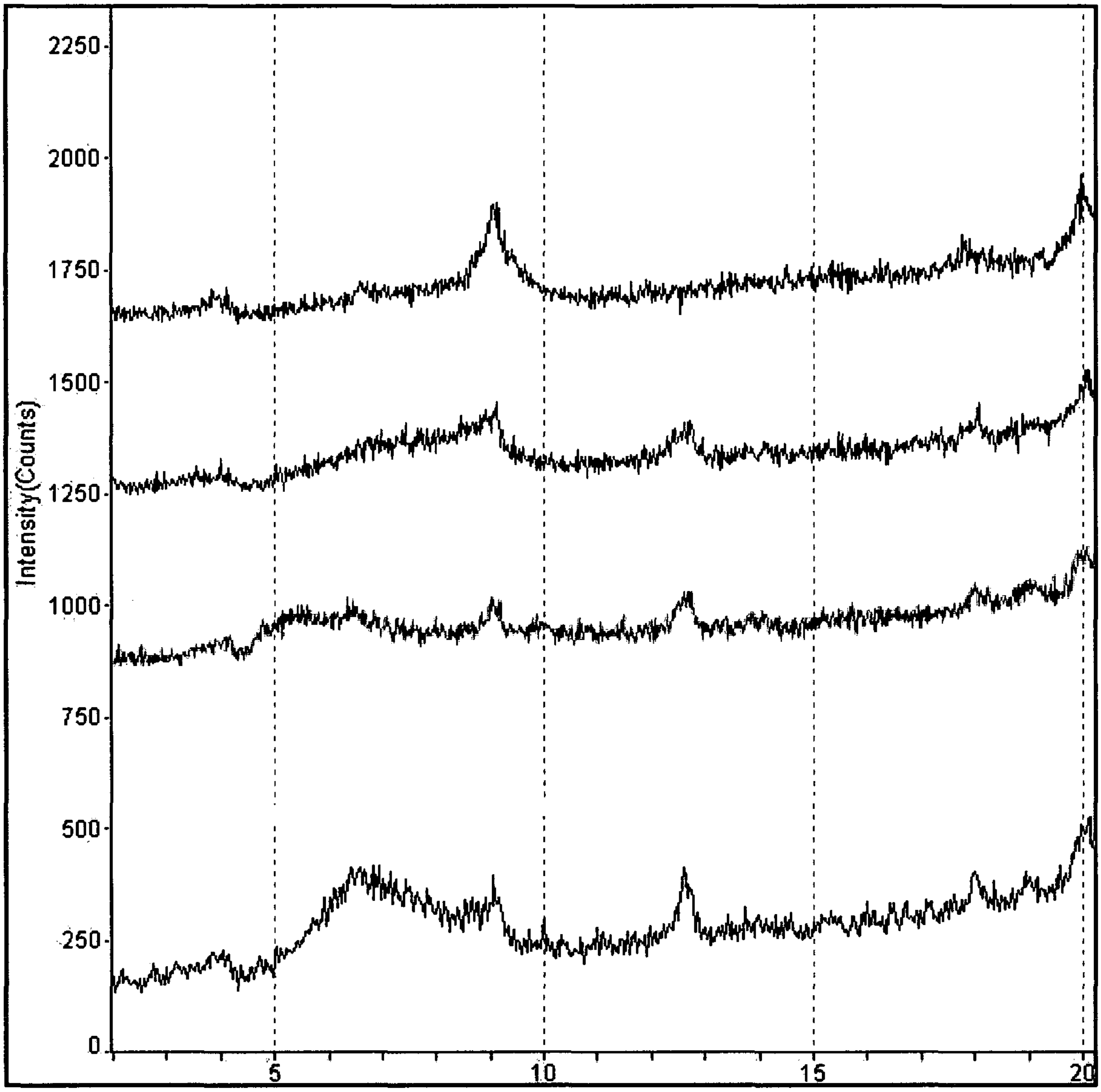
Lou_6L_69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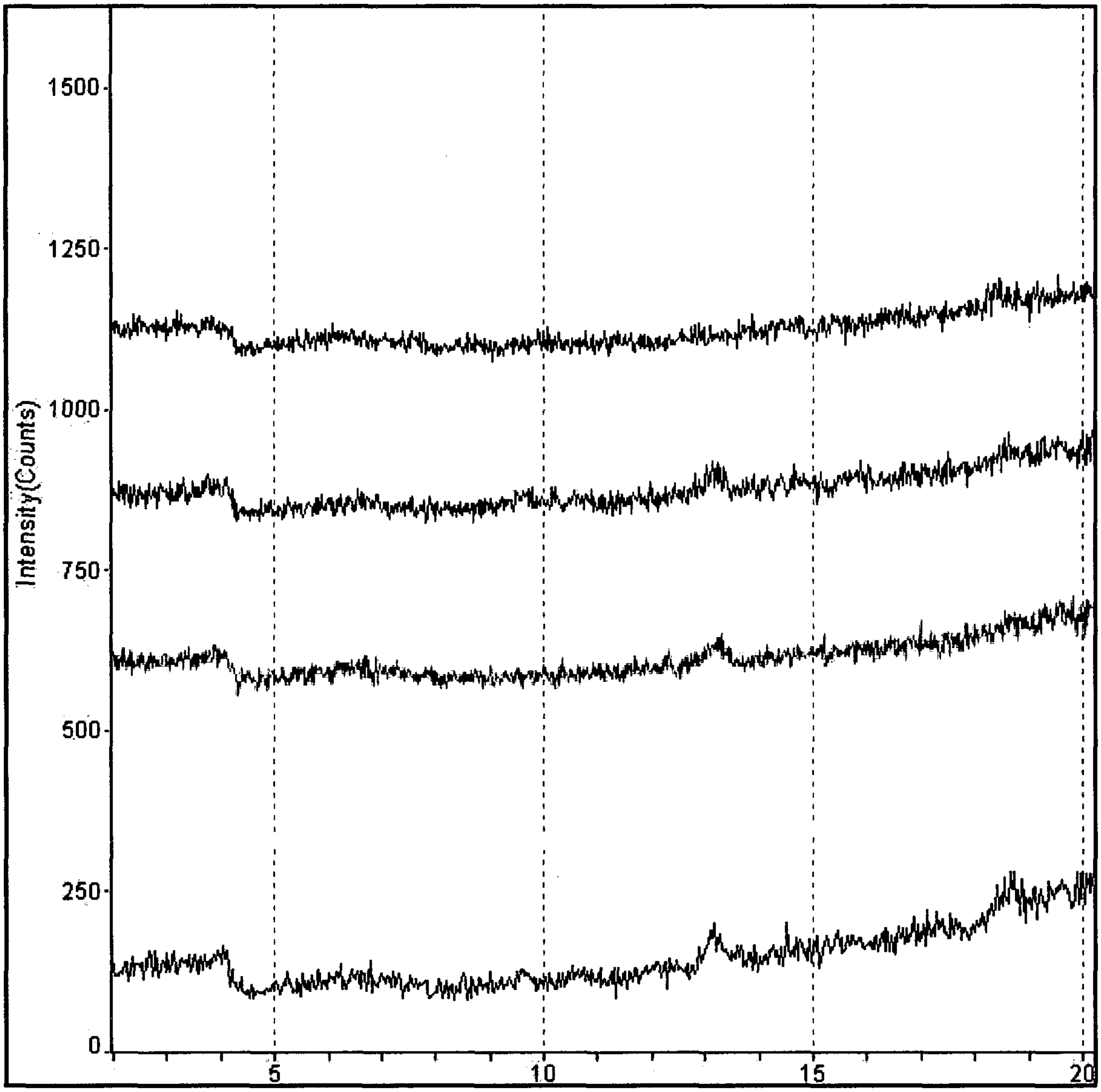
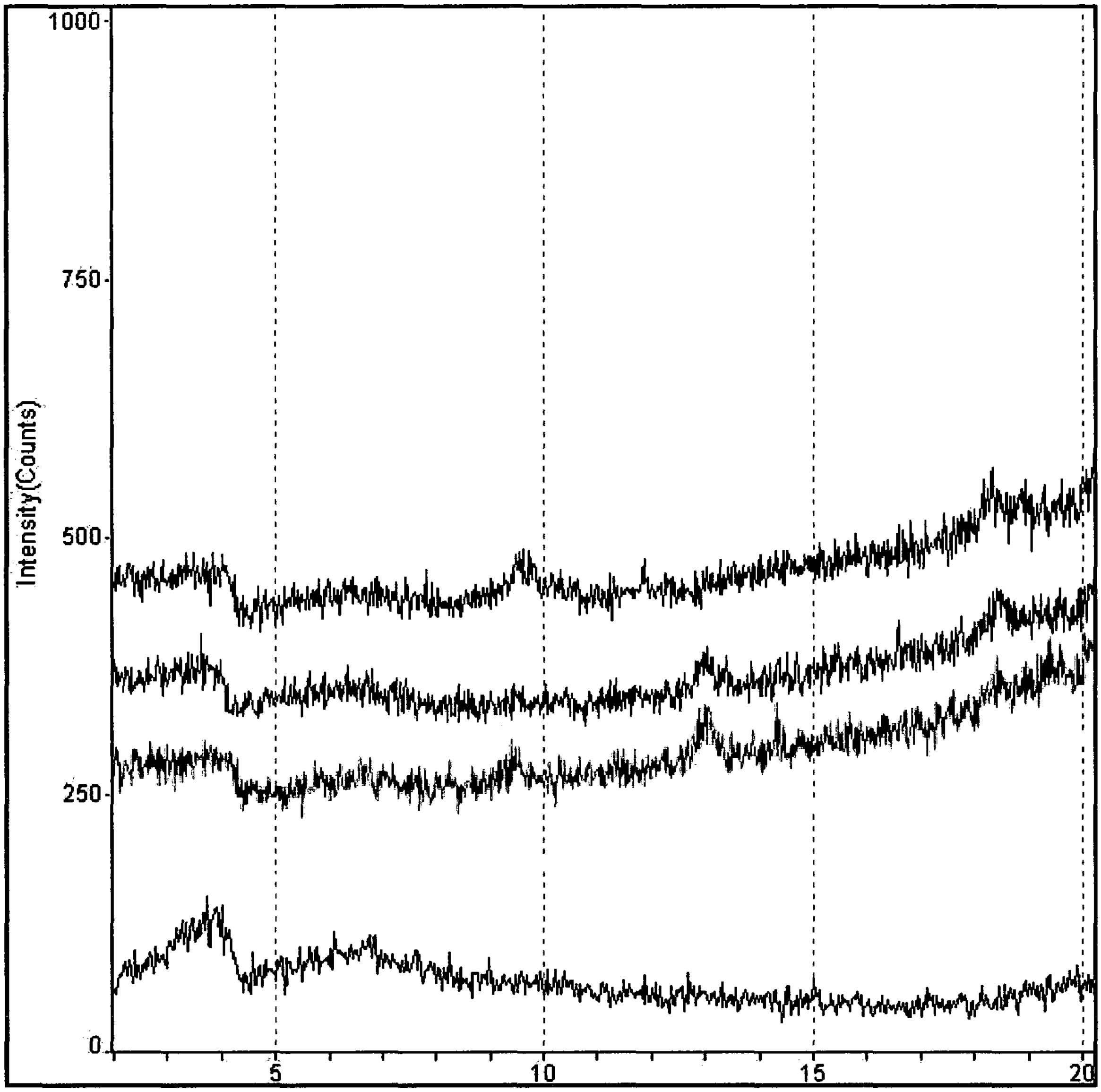
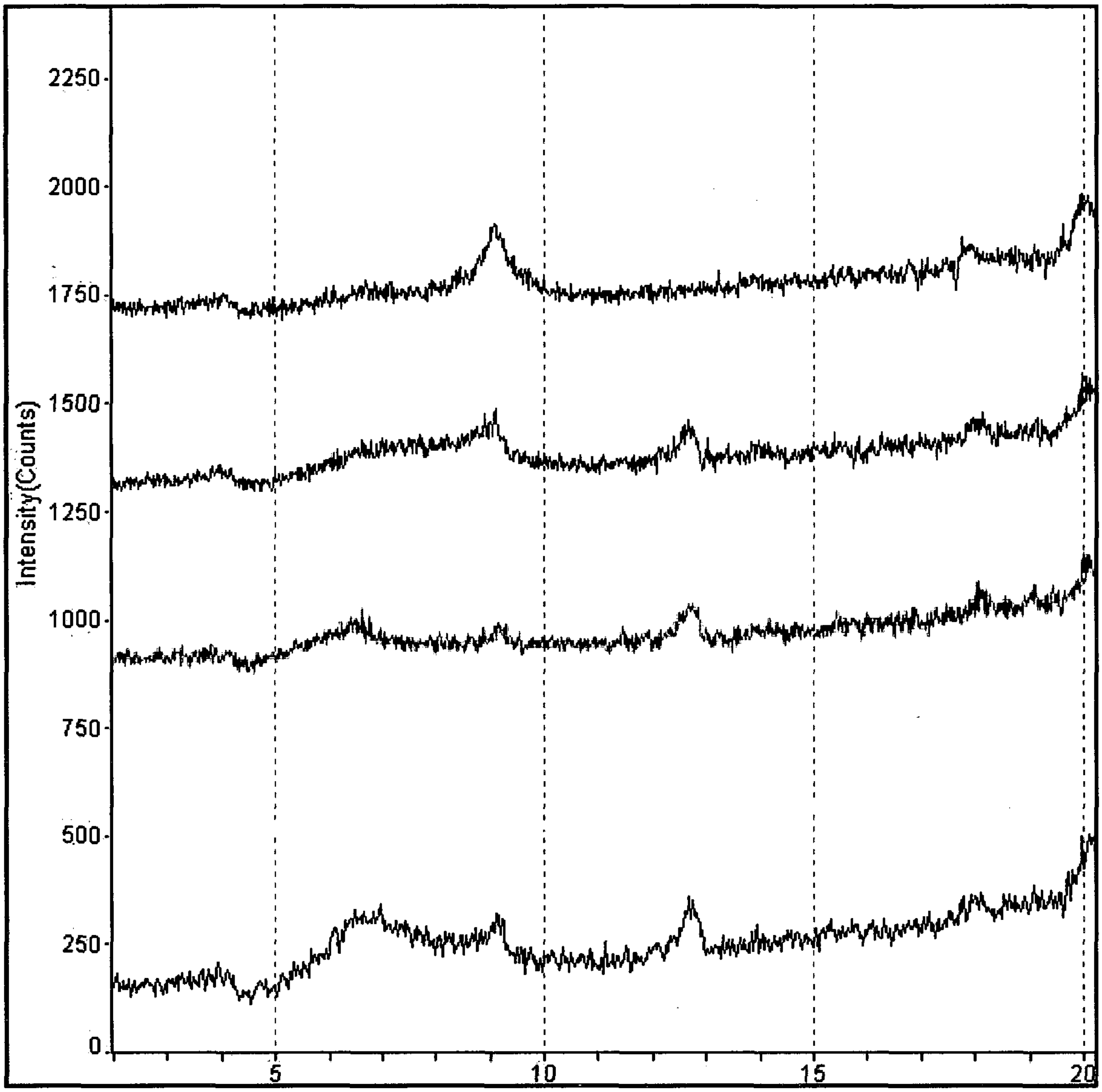
Lou_6L_89



Lou_7L_13



Lou_7L_33



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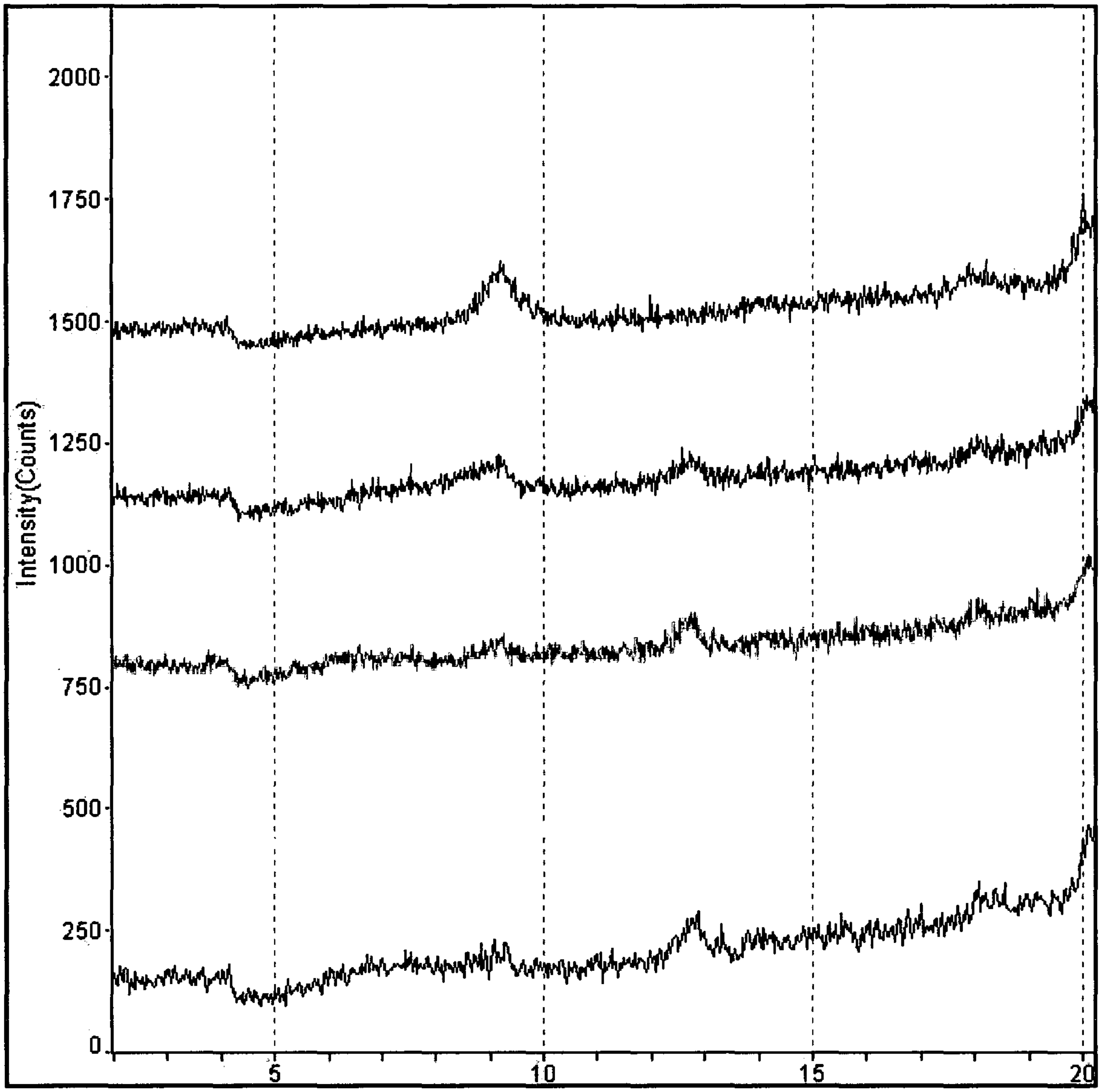
Lou_7L_53



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Intensity(Counts)
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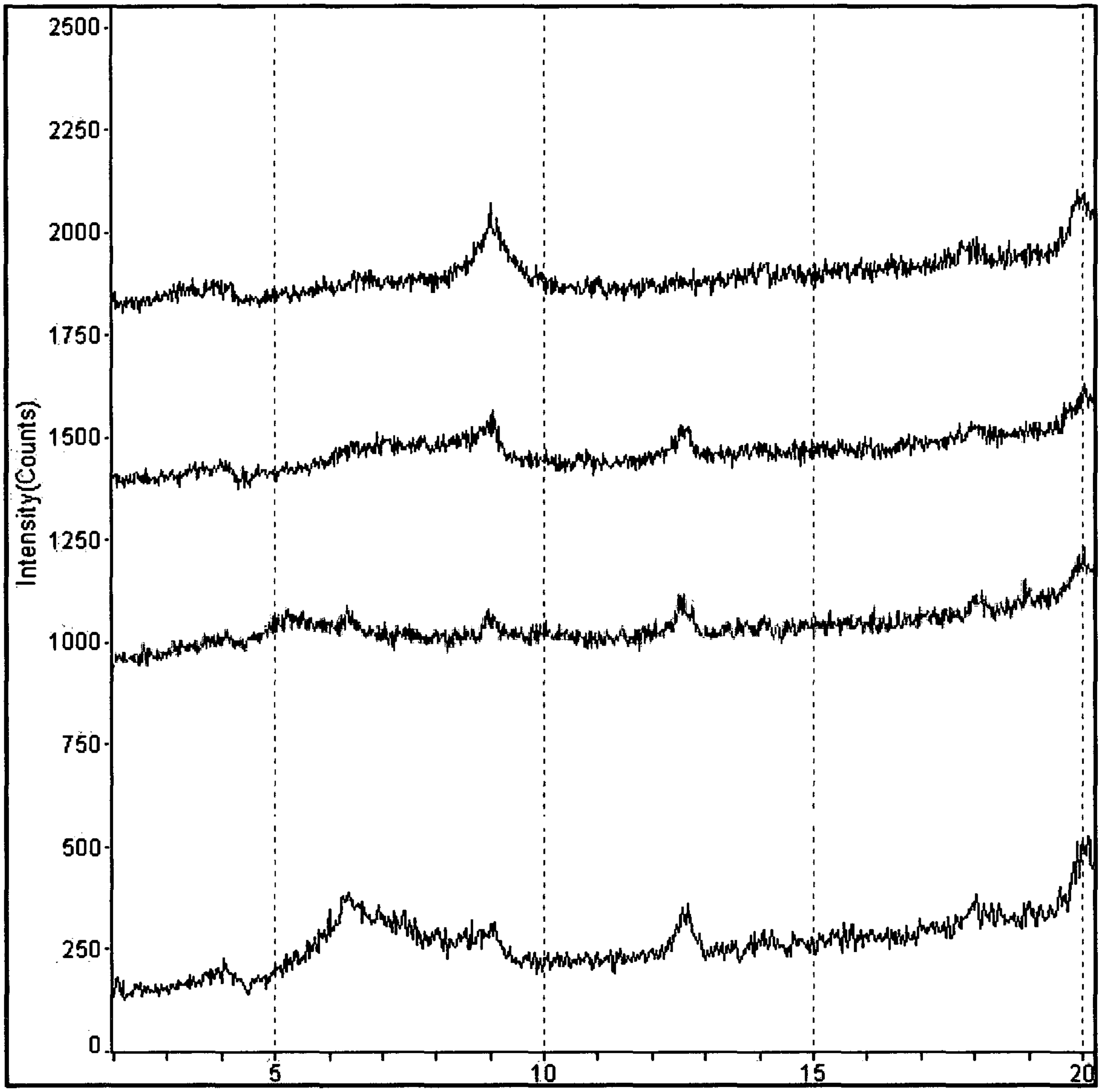
10
15
20

Lou_7L_73



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Intensity(Counts)
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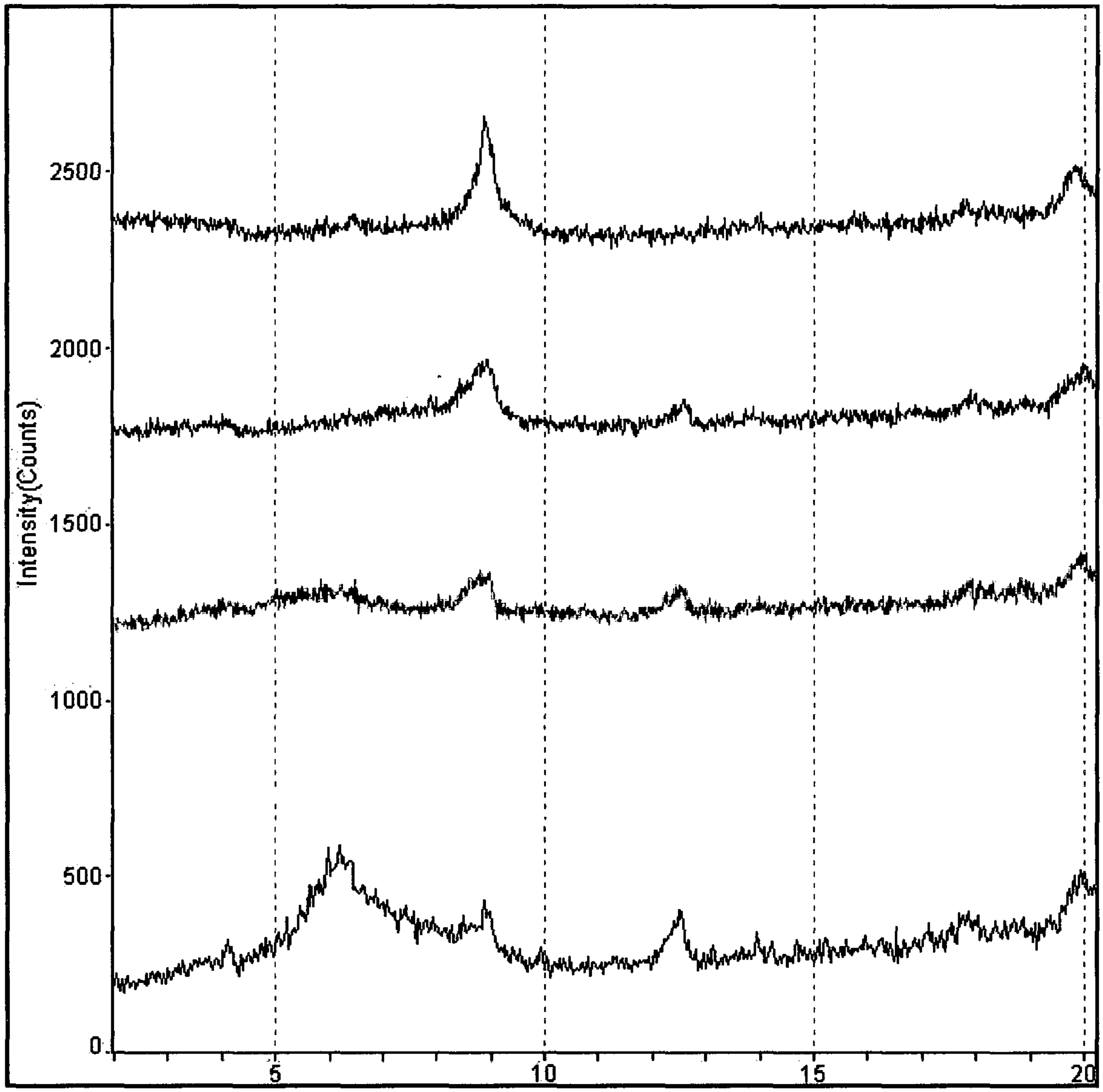
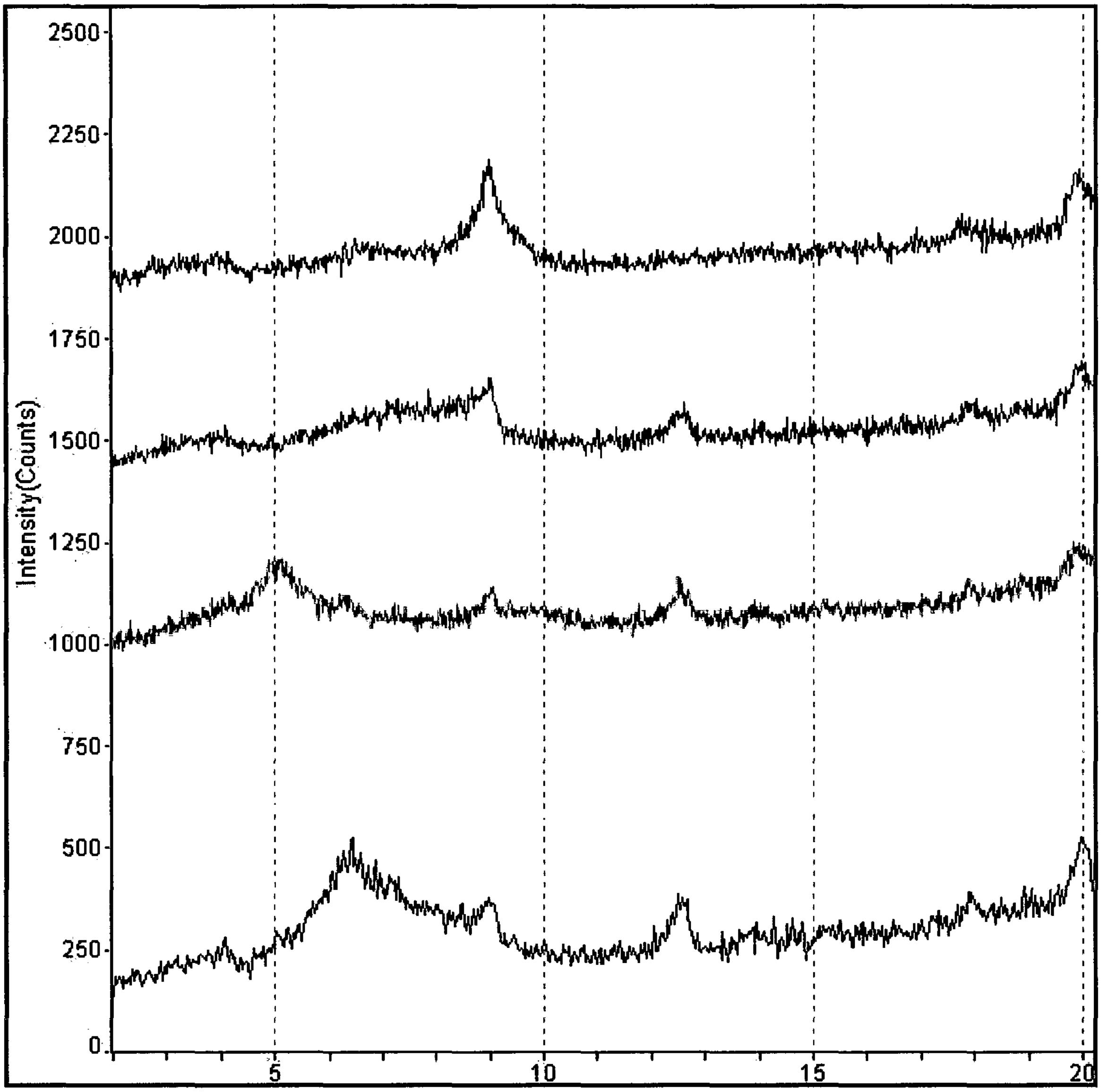
15
20

Lou_7L_93



Lou_8L_59


Intensity(Counts)
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1250
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0
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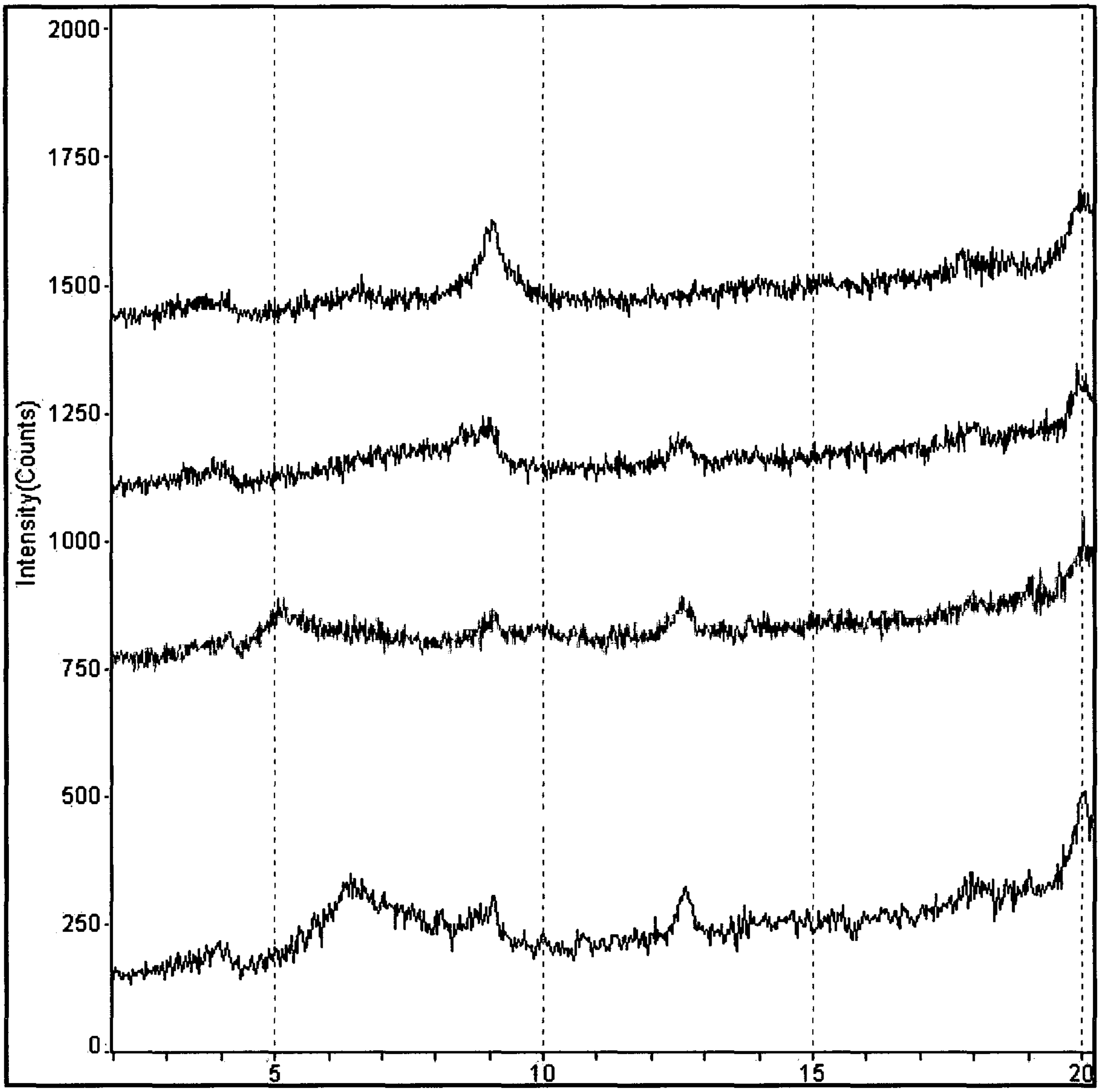
10
15
20

Lou_8L_79



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1250
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750
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250
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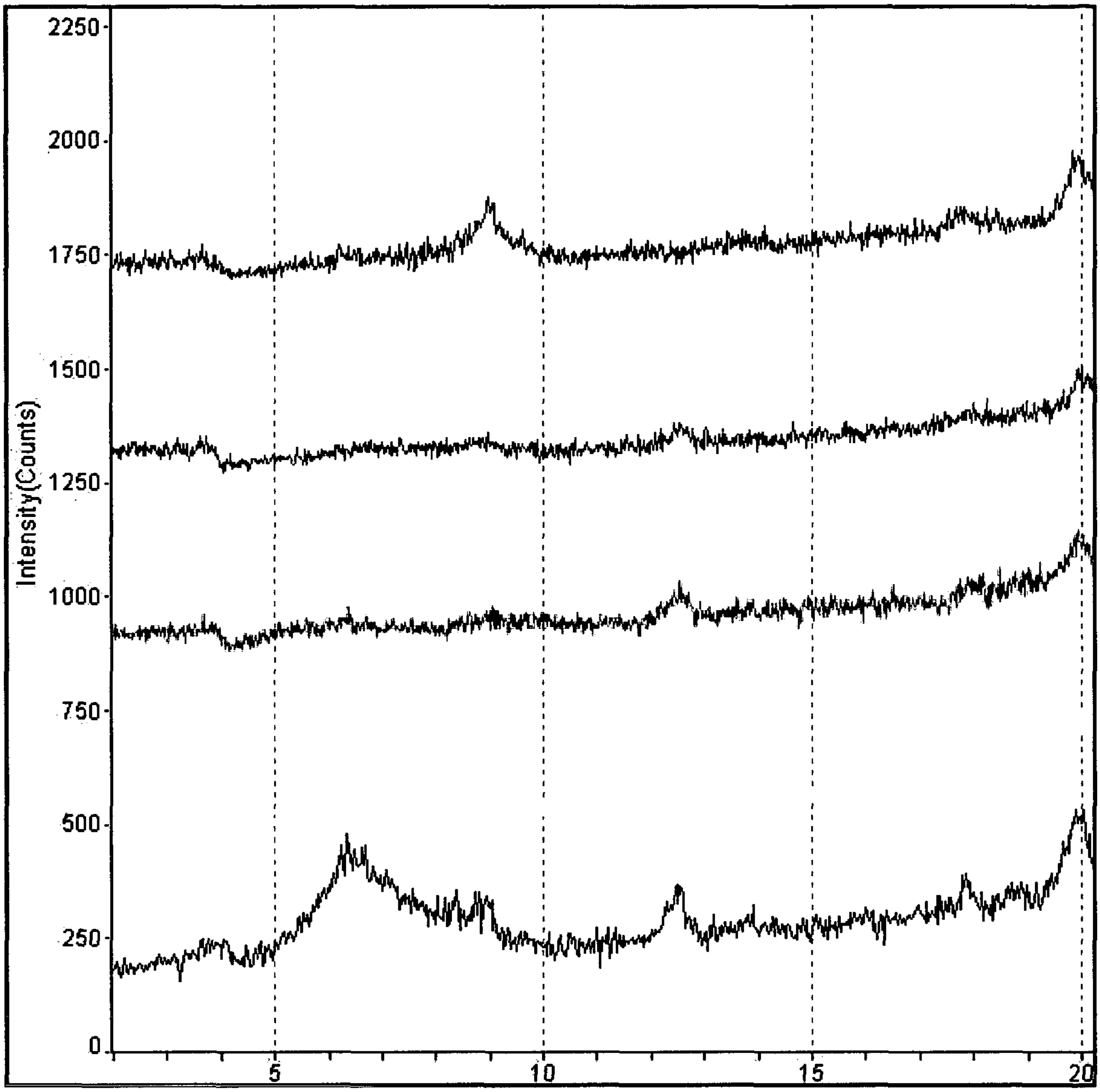
Intensity(Counts)
5
10
15
20

Lou_8L_99



Intensity(Counts)
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15
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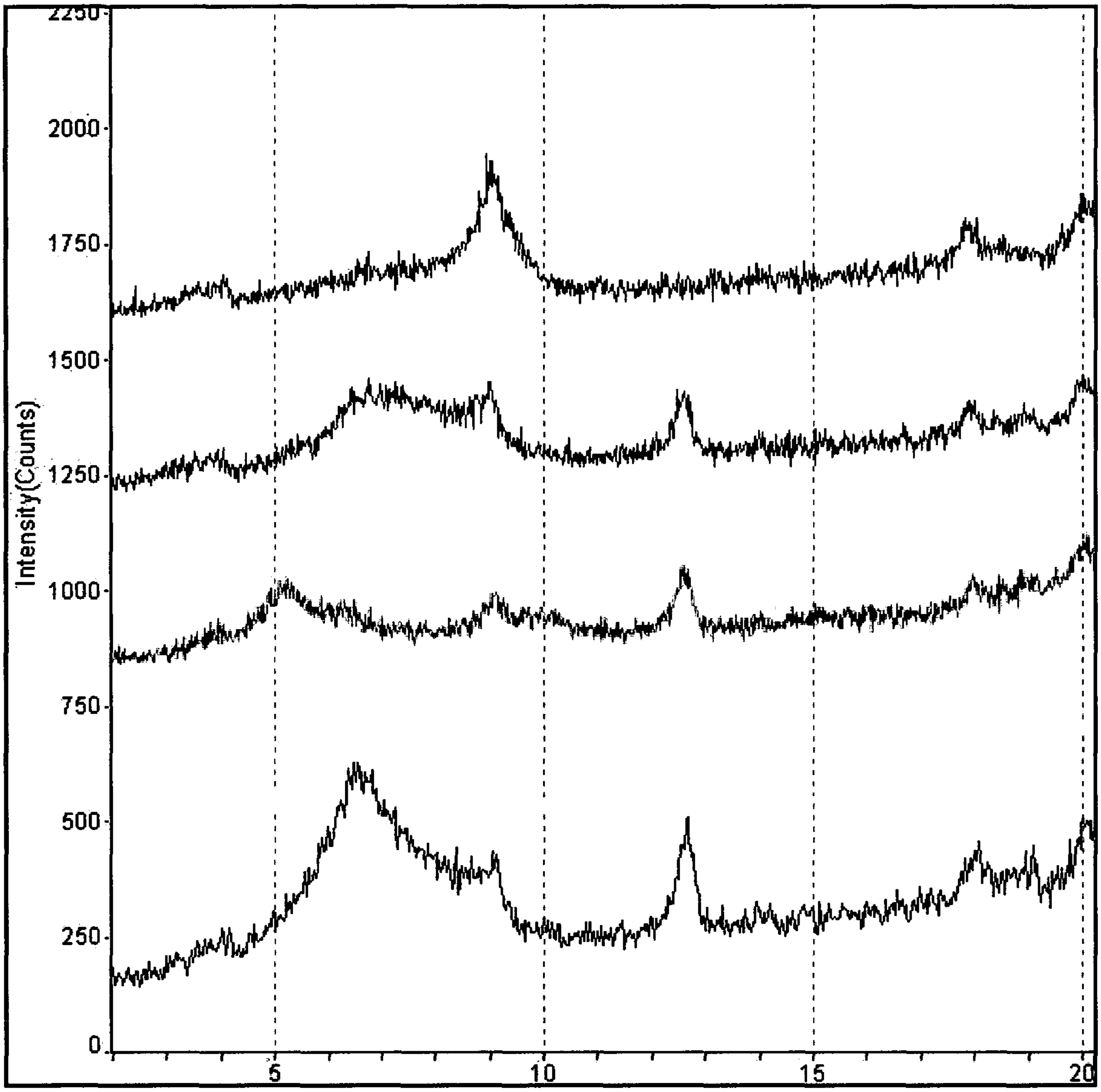
Lou_9L_30



Intensity(Counts)
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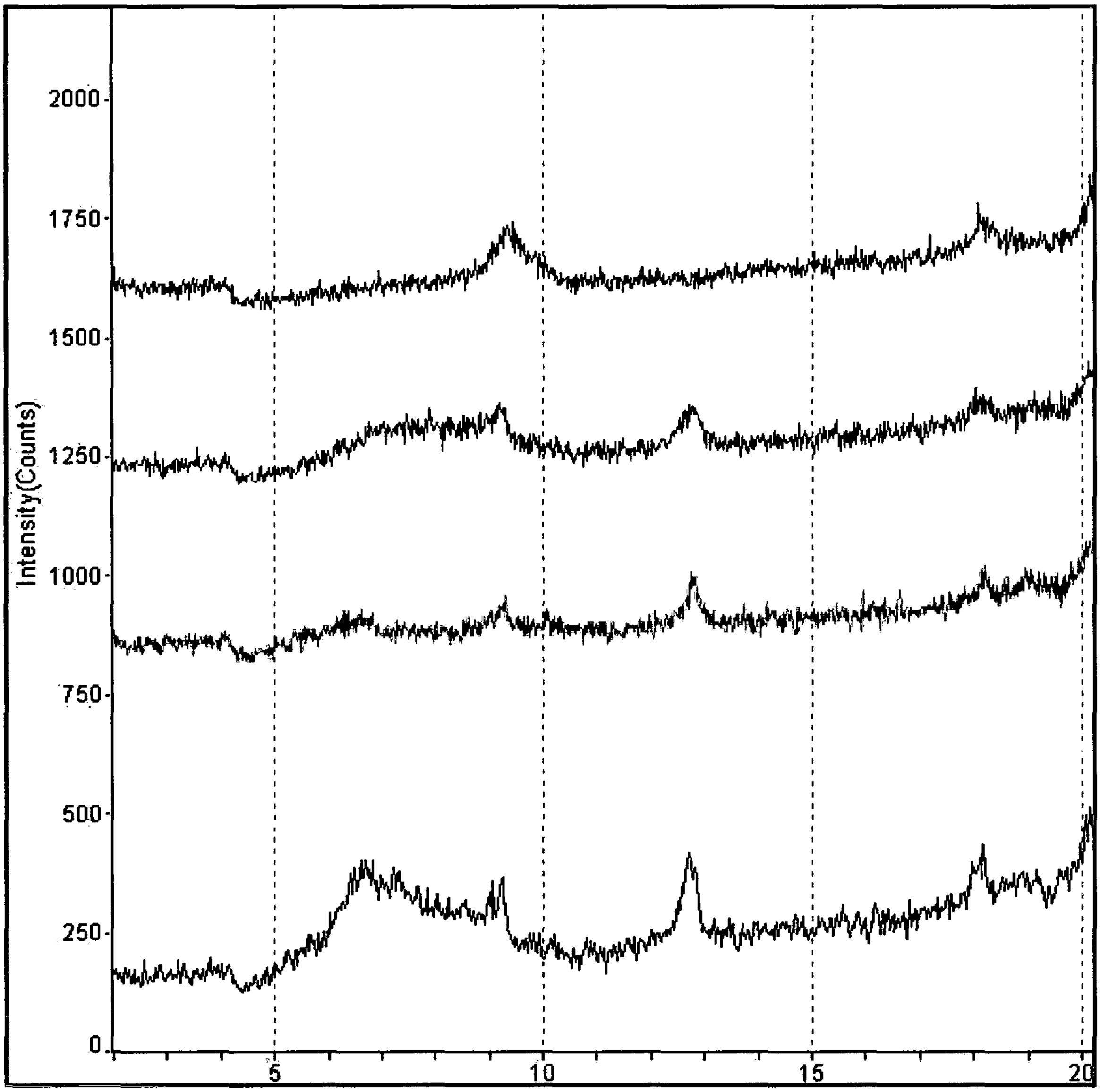
1250
1000
750
500
250
0
5
10
15
20

Lou_9L_50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1250
1000
750
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250
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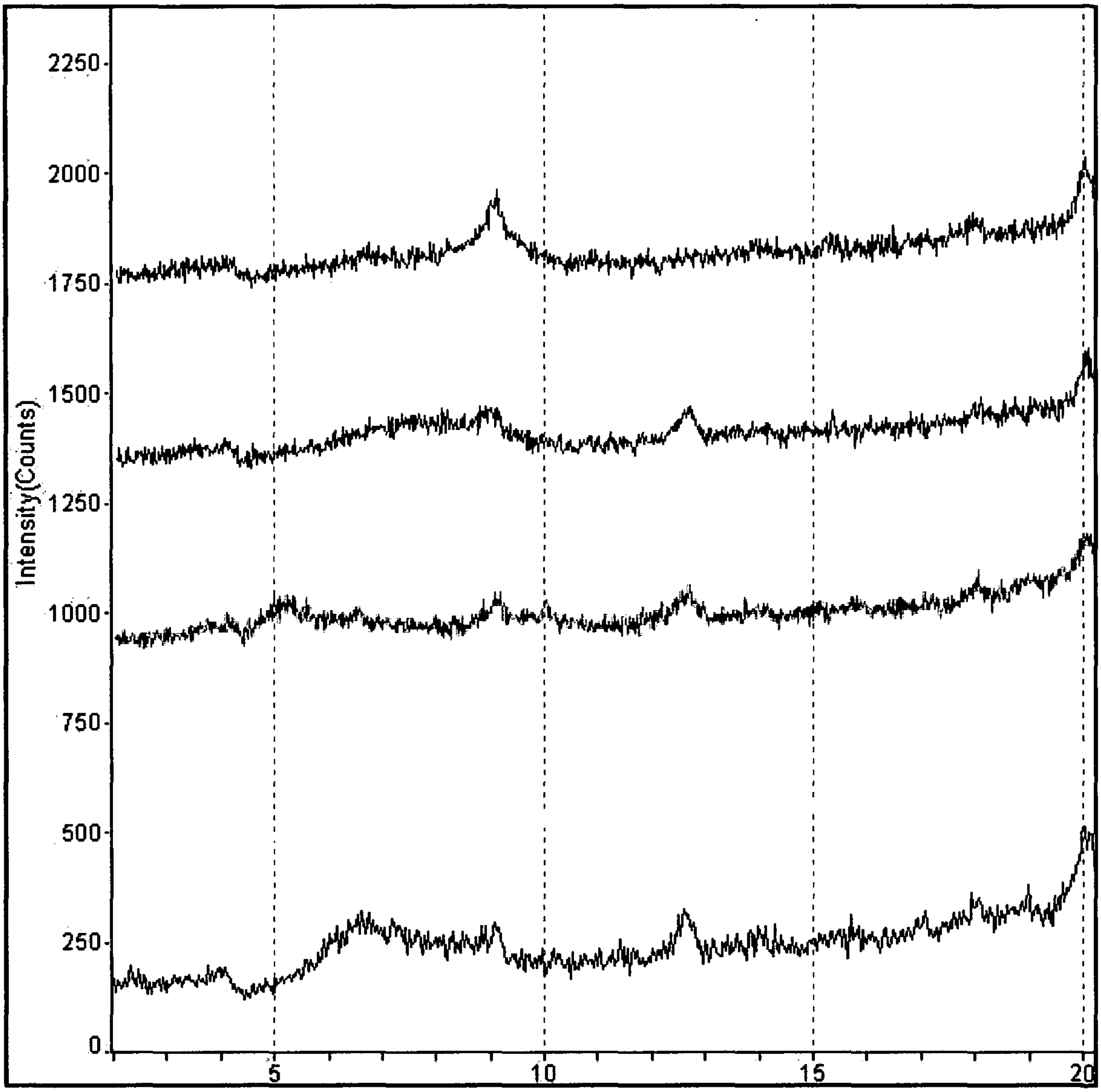
15
20

Lou_9L_70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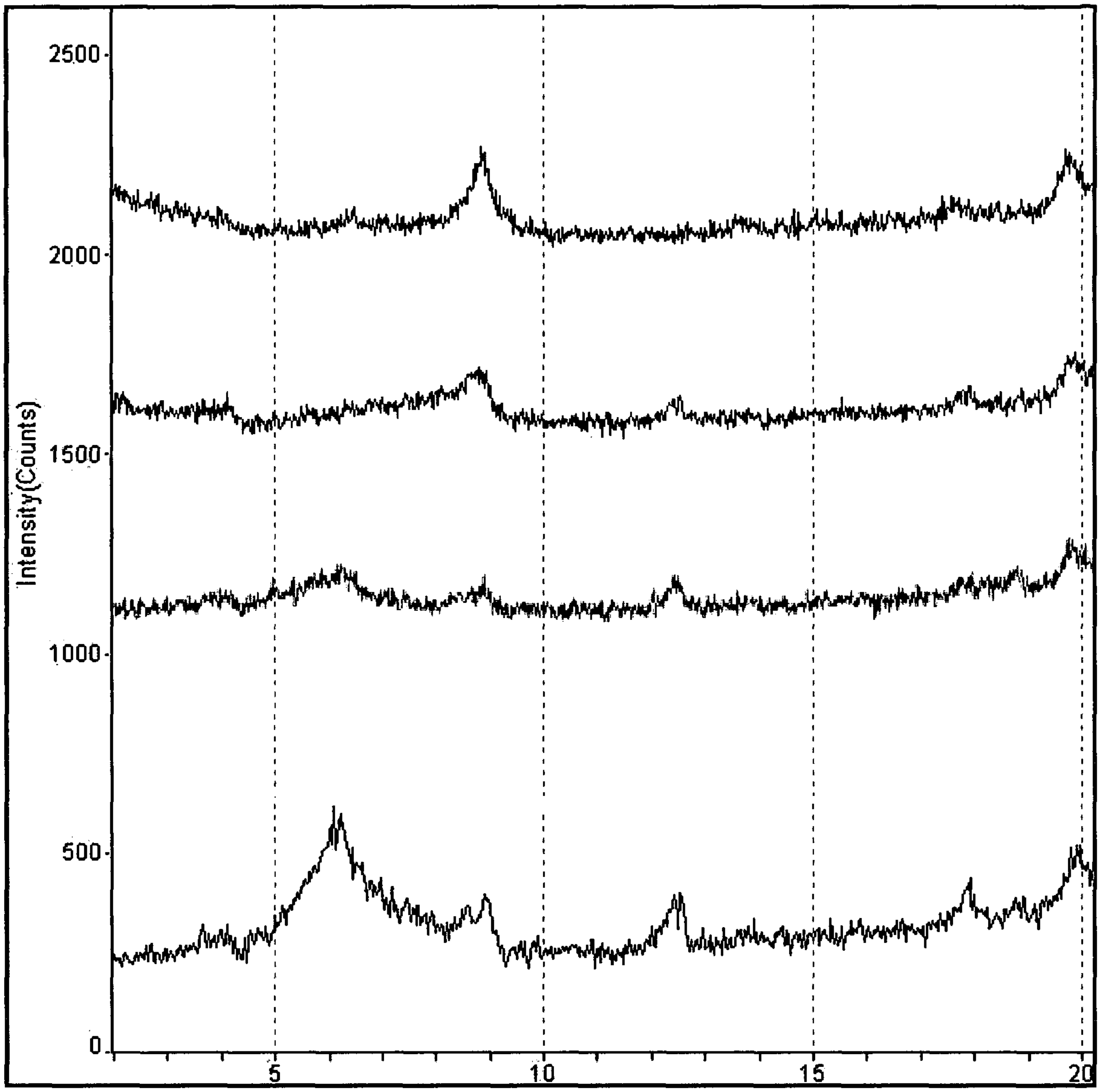
15
20

Lou_9L_90



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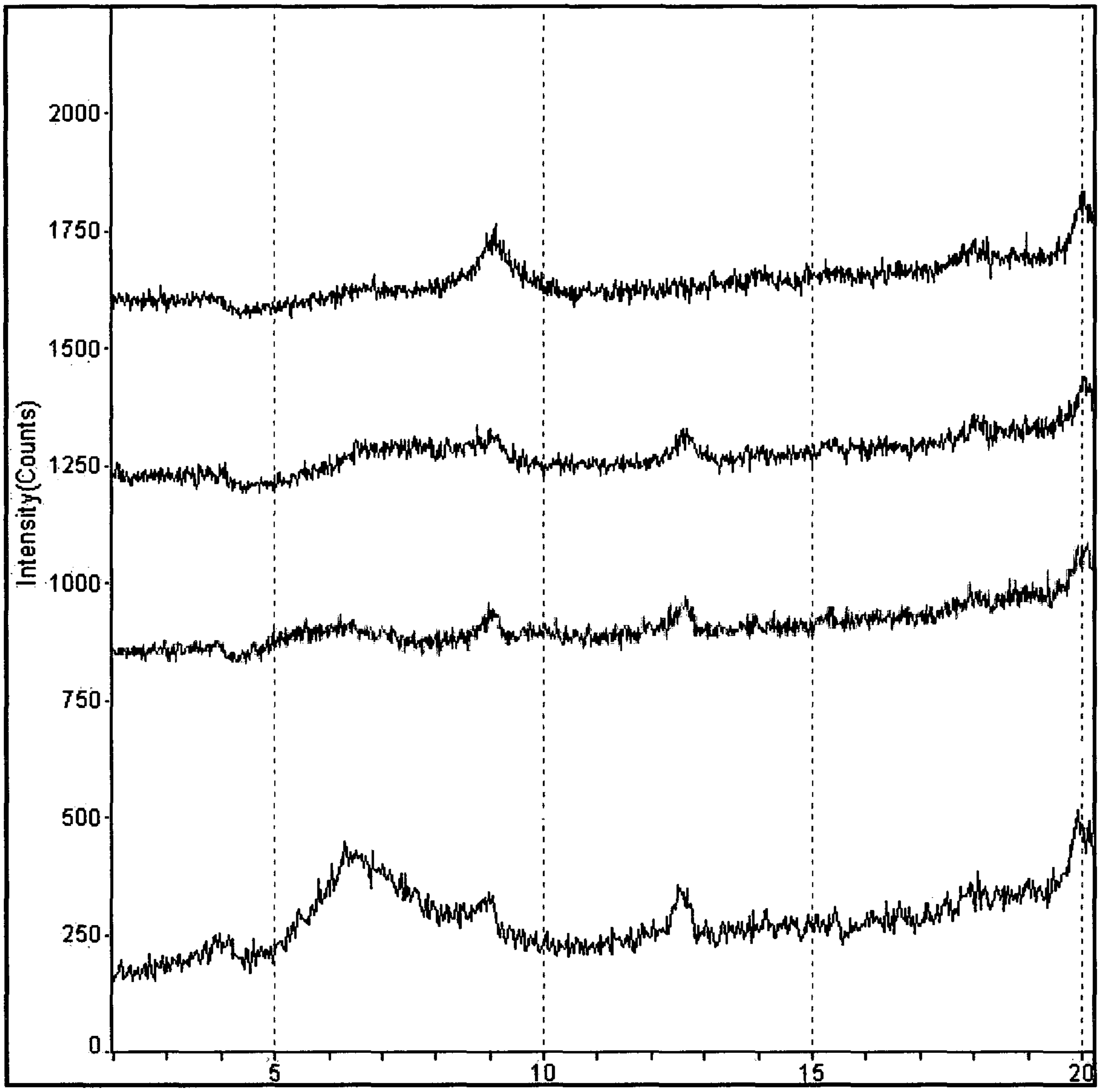

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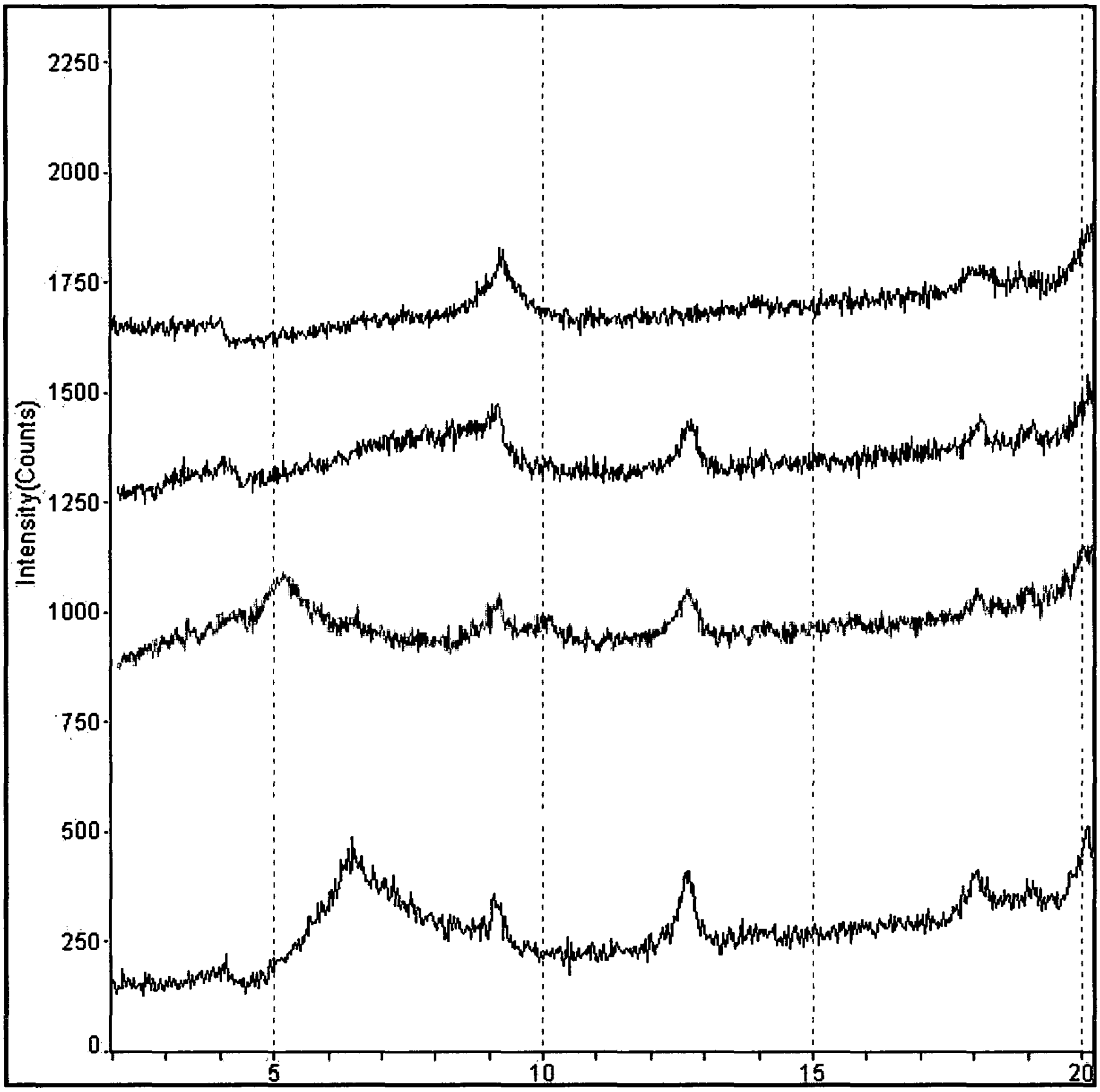
15
20

Lou_10L_46



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750
500
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Intensity(Counts)
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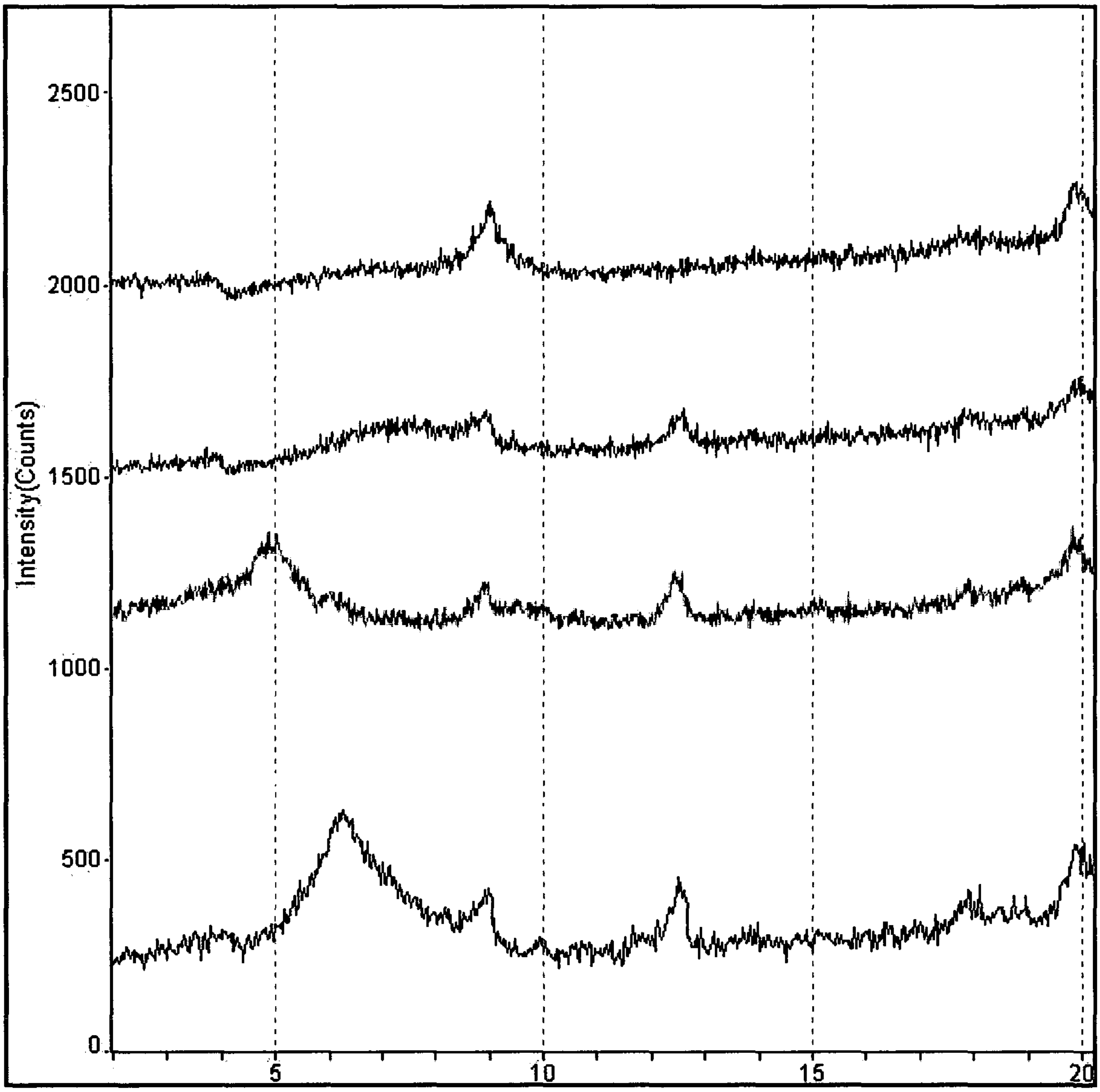
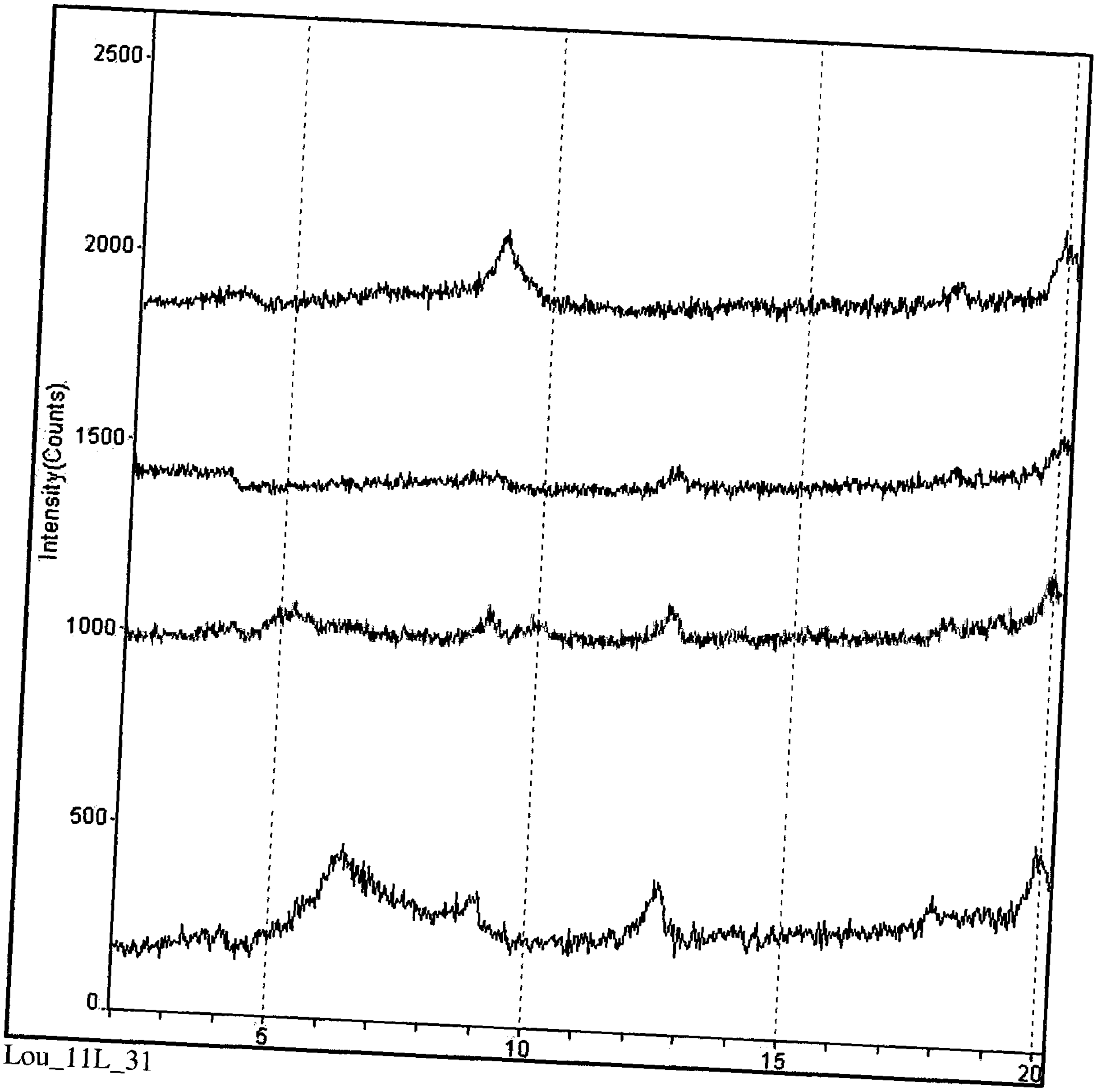
10
15
20

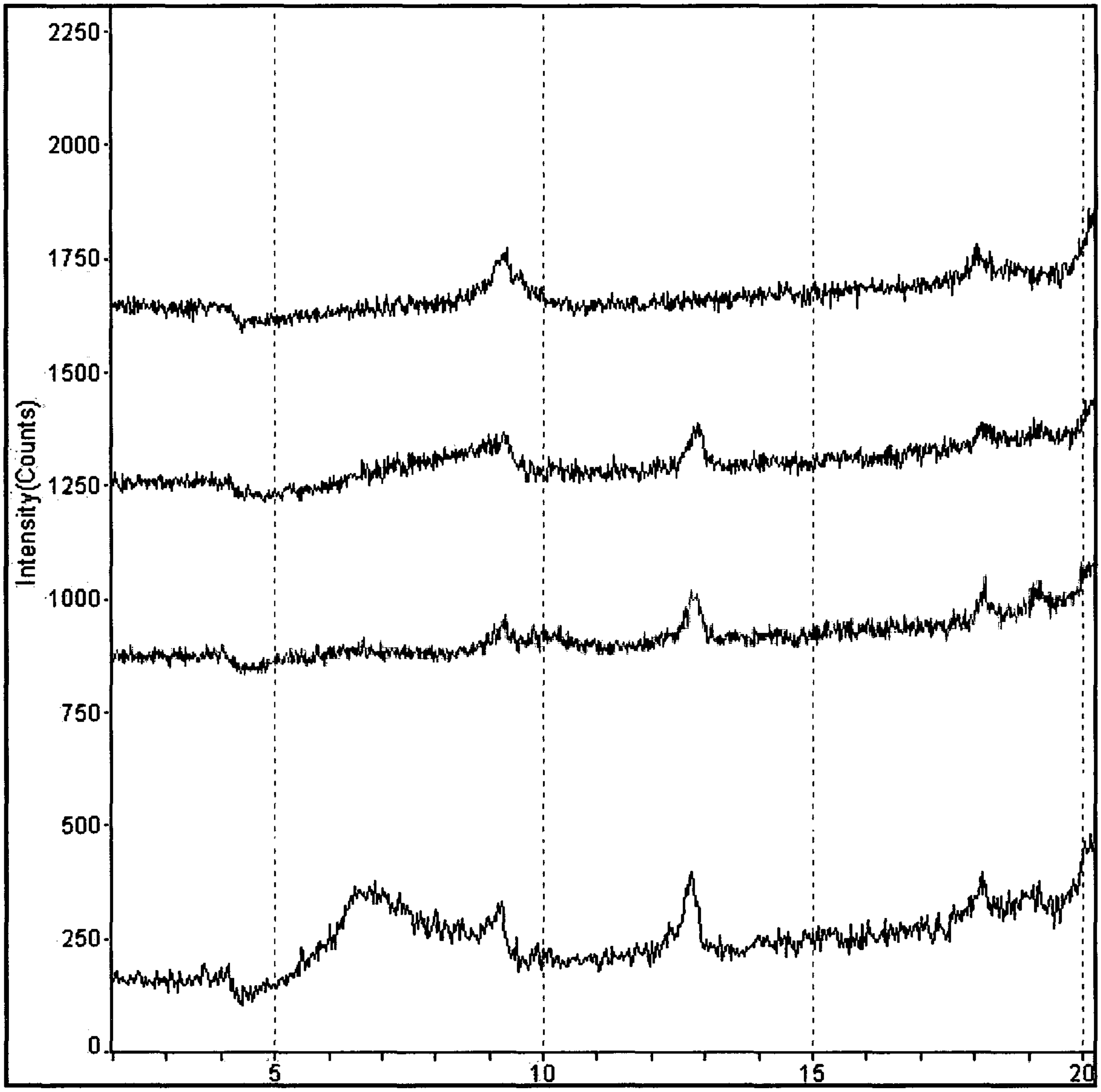
Lou_10L_66



Lou_10L_86



Lou_11L_31


Intensity(Counts)
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750
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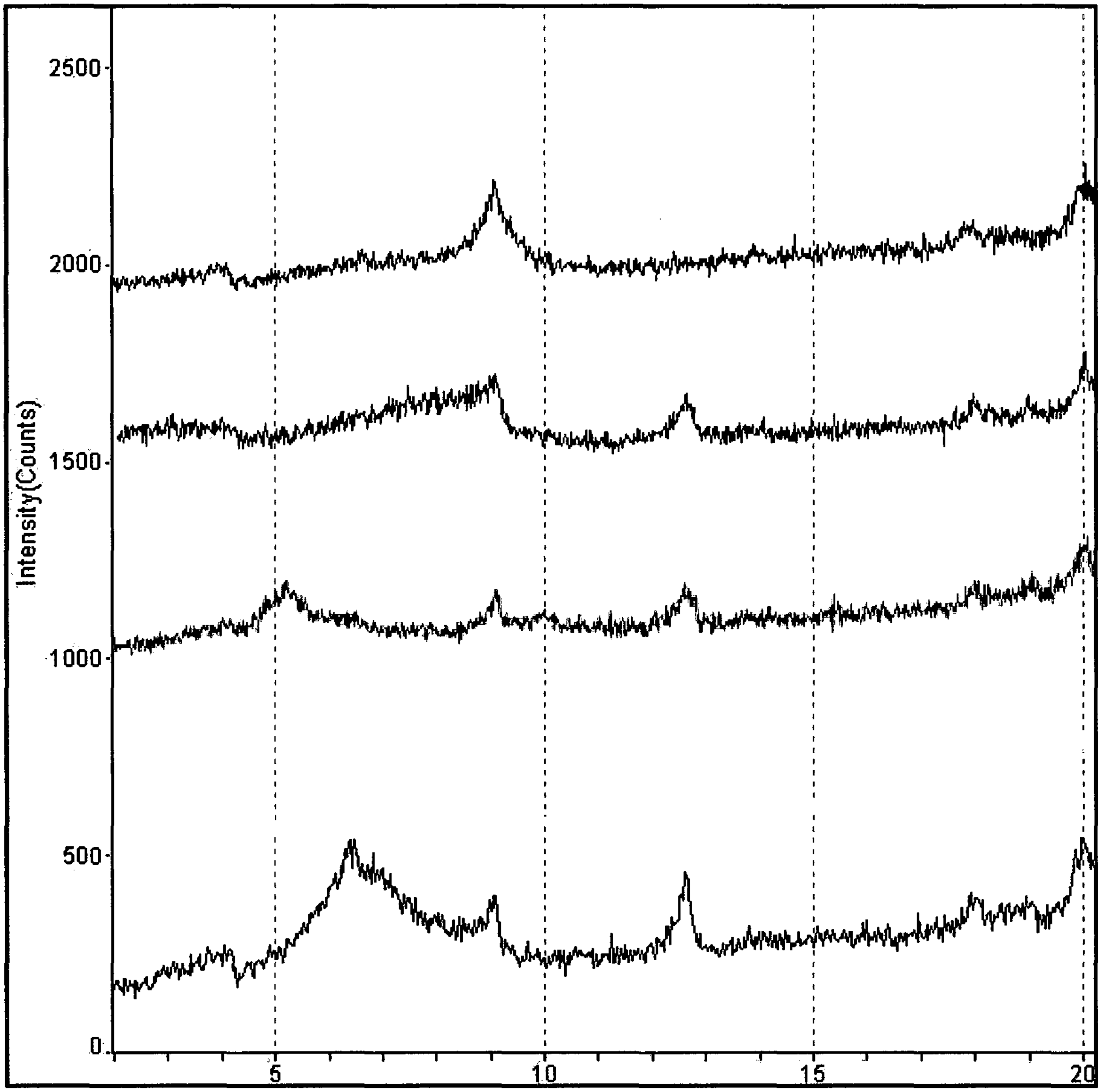
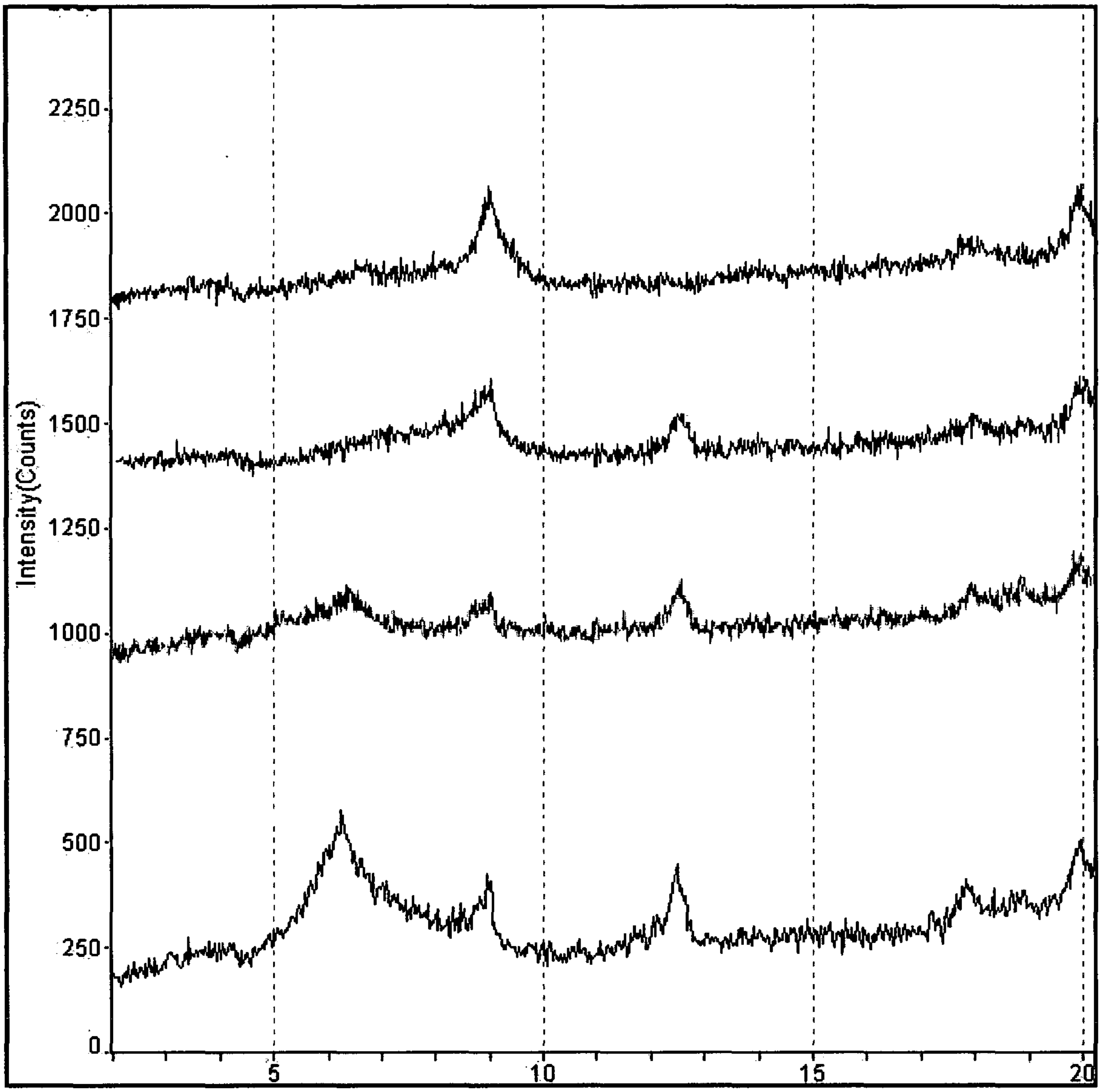
10
15
20

Lou_11L_51



Lou_11L_71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1750
1500
1250
1000
750
500
250
0
Intensity(Counts)
5
10
15
20

Lou_11L_91

Fiddlers Lake Silt Mineralogy Results

Sample	Phase	Lith. Unit	Augite	Biotite	Chlorite	Clinopyroxene	Garnet	Hypersthene	Kyanite	Magnetite	Microcline	Muscovite	Orthoclase	Plagioclase	Quartz	Rutile	Titanite	Tourmaline	Zeolite	Zircon
Fid_1B_14	Post-Glacial	1										Musc								Zirc
Fid_3L_14	Post-Glacial	1									Micro	Musc								
Fid_3L_34	Post-Glacial	1										Musc	O'clase	P'clase						Zirc
Fid_3L_44	Post-Glacial	1									Micro	Musc								
Fid_3L_54	Post-Glacial	1	Aug			C'pyr			Kya	Mag	Micro	Musc		P'clase	Qtz		Titan	Tour		
Fid_3L_70	Transitional	1									Micro	Musc	O'clase	P'clase		Rut				Zirc
Fid_3L_74	Transitional	2		Bio							Micro	Musc			Qtz			Tour		
Fid_3L_84	Transitional	2		Bio		C'pyr					Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour		Zirc
Fid_3L_94	Transitional	2	Aug	Bio		C'pyr		Hyp		Mag	Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_4L_17	Transitional	2				C'pyr					Micro	Musc		P'clase	Qtz		Titan	Tour		Zirc
Fid_4L_27	Transitional	3				C'pyr				Mag	Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_4L_37	Transitional	3								Mag	Micro	Musc			Qtz			Tour		Zirc
Fid_4L_47	Transitional	3				C'pyr					Micro	Musc			Qtz			Tour		
Fid_4L_57	Transitional	3		Bio		C'pyr						Musc	O'clase	P'clase	Qtz			Tour		Zirc
Fid_4L_67	Late-Glacial	3		Bio						Mag		Musc			Qtz			Tour		Zirc
Fid_4L_77	Late-Glacial	4				C'pyr	Garn				Micro	Musc			Qtz	Rut		Tour		
Fid_4L_87	Late-Glacial	4			Chl	C'pyr					Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_4L_97	Late-Glacial	4			Chl	C'pyr	Garn				Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour	Zeo	Zirc
Fid_5L_12	Full-Glacial	4				C'pyr						Musc			Qtz			Tour		
Fid_5L_32	Full-Glacial	4		Bio	Chl	C'pyr						Musc	O'clase	P'clase	Qtz			Tour		
Fid_5L_52	Full-Glacial	4				C'pyr					Micro	Musc			Qtz	Rut		Tour		
Fid_5L_72	Full-Glacial	4			Chl	C'pyr					Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour	Zeo	Zirc
Fid_5L_92	Full-Glacial	4	Aug	Bio	Chl	C'pyr				Mag		Musc			Qtz			Tour	Zeo	Zirc
Fid_6L_21	Full-Glacial	4		Bio	Chl	C'pyr		Hyp			Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_6L_41	Full-Glacial	4		Bio	Chl					Mag	Micro	Musc			Qtz					
Fid_6L_61	Full-Glacial	4	Aug		Chl	C'pyr				Mag	Micro	Musc			Qtz			Tour		Zirc
Fid_6L_81	Full-Glacial	4									Micro	Musc			Qtz			Tour		
Fid_7L_02	Full-Glacial	4	Aug			C'pyr					Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_7L_22	Full-Glacial	4			Chl	C'pyr					Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour		
Fid_7L_32	Full-Glacial	4		Bio	Chl	C'pyr	Garn				Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_7L_42	Full-Glacial	4	Aug	Bio	Chl	C'pyr	Garn	Hyp		Mag	Micro	Musc			Qtz		Titan	Tour		
Fid_7L_62	Full-Glacial	4		Bio	Chl	C'pyr					Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_7L_82	Full-Glacial	4	Aug			C'pyr				Mag	Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_8L_27	Full-Glacial	4	Aug			C'pyr				Mag	Micro	Musc			Qtz			Tour		Zirc
Fid_8L_47	Full-Glacial	4	Aug		Chl	C'pyr				Mag	Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_8L_67	Full-Glacial	4	Aug	Bio	Chl	C'pyr				Mag	Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_8L_87	Full-Glacial	4			Chl	C'pyr					Micro	Musc			Qtz		Titan	Tour		Zirc
Fid_9L_09	Full-Glacial	4					Garn			Mag		Musc	O'clase	P'clase	Qtz			Tour		Zirc
Fid_9L_29	Full-Glacial	4						Hyp												
Fid_9L_49	Full-Glacial	4		Bio	Chl					Mag		Musc	O'clase	P'clase	Qtz			Tour	Zeo	
Fid_9L_69	Full-Glacial	4	Aug	Bio	Chl	C'pyr					Micro	Musc			Qtz		Titan	Tour	Zeo	Zirc
Fid_9L_89	Full-Glacial	4	Aug	Bio	Chl	C'pyr				Mag	Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour	Zeo	Zirc
Fid_9L_95	Full-Glacial	4		Bio	Chl	C'pyr	Garn					Musc	O'clase	P'clase	Qtz			Tour		Zirc
Fid_9L_97	Full-Glacial	5	Aug		Chl	C'pyr				Mag	Micro	Musc	O'clase	P'clase	Qtz		Titan	Tour		Zirc

Louis Lake Silt Mineralogy Results

sample	Phase	Lith. Unit	Apatite	Augite	Biotite	Chlorite	Clinopyroxene	Garne	Hornblend	Hypersthene	Kyanite	Magnetite	Microclin	Muscovit	Olivine	Orthoclas	Orthopyroxene	Plagioclas	Quartz	Rutile	Titanite	Tourmaline	Zircon
Lou_1L_70	Post-Glacial	1			Bio						Kya	Mag	Micro	Musc					Qua			Tour	Zirc
Lou_1L_80	Post-Glacial	1			Bio							Mag	Micro	Musc					Qua			Tour	Zirc
Lou_1L_90	Post-Glacial	1												Musc		O'Clase		P'clase				Tour	Zirc
Lou_2L_10	Post-Glacial	1			Bio									Musc					Qua			Tour	Zirc
Lou_2L_20	Post-Glacial	1			Bio			Garn				Mag	Micro	Musc					Qua	Rut	Titan	Tour	Zirc
Lou_2L_30	Post-Glacial	1			Bio	Chl							Micro	Musc		O'Clase		P'clase		Rut		Tour	Zirc
Lou_2L_40	Post-Glacial	1		Aug	Bio		Clino					Mag	Micro	Musc	Oliv	O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_2L_50	Post-Glacial	1		Aug			Clino	Garn				Mag	Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_2L_60	Post-Glacial	1											Micro	Musc		O'Clase	O'pyr	P'clase				Tour	Zirc
Lou_2L_70	Post-Glacial	1			Bio									Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_2L_80	Post-Glacial	1							Hornb	Hyp	Kya		Micro	Musc		O'Clase		P'clase				Tour	Zirc
Lou_2L_90	Post-Glacial	1											Micro	Musc		O'Clase		P'clase				Tour	Zirc
Lou_2L_100	Post-Glacial	1			Bio				Hornb			Mag	Micro	Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_3L_10	Post-Glacial	1		Aug			Clino					Mag	Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_3L_20	Post-Glacial	1											Micro	Musc		O'Clase		P'clase					Zirc
Lou_3L_30	Post-Glacial	1																					Zirc
Lou_3L_40	Post-Glacial	1		Aug			Clino				Kya	Mag	Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_3L_50	Post-Glacial	1		Aug	Bio		Clino					Mag	Micro	Musc					Qua	Rut	Titan	Tour	Zirc
Lou_3L_60	Post-Glacial	1								Hyp			Micro	Musc		O'Clase		P'clase	Qua	Rut		Tour	Zirc
Lou_3L_70	Post-Glacial	1									Kya			Musc									
Lou_3L_80	Post-Glacial	1					Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	
Lou_4L_02	Post-Glacial	1											Micro	Musc					Qua			Tour	Zirc
Lou_4L_12	Post-Glacial	1		Aug			Clino				Kya		Micro	Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_4L_22	Post-Glacial	1			Bio							Mag	Micro	Musc					Qua			Tour	Zirc
Lou_4L_32	Post-Glacial	1		Aug			Clino					Mag	Micro	Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_4L_42	Transitional	1			Bio		Clino					Mag	Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_4L_52	Transitional	1	Apa							Hyp			Micro	Musc	Oliv				Qua			Tour	Zirc
Lou_4L_62	Transitional	1		Aug			Clino			Hyp		Mag		Musc		O'Clase		P'clase	Qua			Tour	
Lou_4L_72	Transitional	1		Aug	Bio		Clino					Mag	Micro	Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_4L_82	Transitional	2		Aug			Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_4L_92	Transitional	2			Bio		Clino			Hyp	Kya		Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_4L_102	Transitional	2			Bio		Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_5L_11	Late-Glacial	2		Aug	Bio		Clino					Mag	Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_5L_21	Late-Glacial	2		Aug	Bio		Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	
Lou_5L_31	Late-Glacial	3			Bio									Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_5L_41	Late-Glacial	3		Aug	Bio		Clino					Mag		Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_5L_51	Late-Glacial	3		Aug			Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_5L_61	Full-Glacial	3			Bio								Micro	Musc					Qua			Tour	Zirc
Lou_5L_71	Full-Glacial	3					Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_5L_81	Full-Glacial	3		Aug			Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_5L_91	Full-Glacial	3		Aug			Clino					Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_6L_09	Full-Glacial	3		Aug			Clino					Mag	Micro	Musc					Qua			Tour	Zirc
Lou_6L_29	Full-Glacial	4					Clino						Micro	Musc		O'Clase		P'clase	Qua		Titan	Tour	Zirc
Lou_6L_49	Full-Glacial	4		Aug			Clino	Garn					Micro	Musc					Qua		Titan	Tour	
Lou_6L_69	Full-Glacial	4			Bio	Chl						Mag	Micro	Musc					Qua			Tour	Zirc
Lou_6L_89	Full-Glacial	4		Aug		Chl	Clino					Mag	Micro	Musc					Qua	Rut		Tour	Zirc
Lou_7L_13	Full-Glacial	4					Clino						Micro	Musc					Qua	Rut	Titan	Tour	Zirc
Lou_7L_33	Full-Glacial	4									Kya												Zirc
Lou_7L_53	Full-Glacial	4				Chl							Micro			O'Clase		P'clase	Qua			Tour	Zirc
Lou_7L_73	Full-Glacial	4									Kya			Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_7L_93	Full-Glacial	4				Chl	Clino			Hyp			Micro	Musc					Qua		Titan	Tour	Zirc
Lou_8L_59	Full-Glacial	4		Aug	Bio	Chl	Clino					Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_8L_79	Full-Glacial	4				Chl						Mag	Micro	Musc		O'Clase		P'clase	Qua			Tour	
Lou_8L_99	Full-Glacial	4		Aug	Bio		Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_9L_30	Full-Glacial	4				Chl	Clino	Garn					Micro	Musc					Qua		Titan	Tour	Zirc
Lou_9L_50	Full-Glacial	4		Aug	Bio	Chl	Clino					Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_9L_70	Full-Glacial	4				Chl	Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_9L_90	Full-Glacial	4					Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_10L_26	Full-Glacial	4			Bio	Chl	Clino						Micro	Musc					Qua		Titan	Tour	Zirc
Lou_10L_46	Full-Glacial	4				Chl				Hyp	Kya	Mag		Musc					Qua			Tour	Zirc
Lou_10L_66	Full-Glacial	4		Aug	Bio	Chl	Clino					Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_10L_86	Full-Glacial	4		Aug	Bio	Chl	Clino					Mag		Musc		O'Clase		P'clase	Qua			Tour	Zirc
Lou_11L_31	Full-Glacial	4		Aug	Bio	Chl	Clino					Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_11L_51	Full-Glacial	4				Chl	Clino							Musc					Qua			Tour	
Lou_11L_71	Full-Glacial	4		Aug		Chl	Clino			Hyp		Mag	Micro	Musc					Qua		Titan	Tour	Zirc
Lou_11L_91	Full-Glacial	4		Aug		Chl	Clino					Mag		Musc					Qua			Tour	Zirc

APPENDIX C

LOSS-ON-IGNITION

Fiddlers Lake Organic Matter Content

Sample	Lith. Unit	Phase	Depth (cm)	Organic Matter Content
Fid_1B_14	1	Post-Glacial	92	30.18
Fid_1B_24	1	Post-Glacial	102	36.88
Fid_1B_34	1	Post-Glacial	112	36.34
Fid_1B_44	1	Post-Glacial	122	31.66
Fid_1B_54	1	Post-Glacial	132	25.65
Fid_1B_64	1	Post-Glacial	142	24.79
Fid_1B_74	1	Post-Glacial	152	30.54
Fid_1B_84	1	Post-Glacial	162	31.41
Fid_1B_94	1	Post-Glacial	172	31.81
Fid_3L_04	1	Post-Glacial	182	35.81
Fid_3L_14	1	Post-Glacial	192	34.67
Fid_3L_24	1	Post-Glacial	202	36.48
Fid_3L_34	1	Post-Glacial	212	39.18
Fid_3L_44	1	Post-Glacial	222	35.54
Fid_3L_54	1	Post-Glacial	232	43.93
Fid_3L_64	1	Transitional	242	48.87
Fid_3L_70	1	Transitional	248	38.34
Fid_3L_74	2	Transitional	252	15.28
Fid_3L_84	2	Transitional	262	13.98
Fid_3L_94	2	Transitional	272	14.48
Fid_4L_07	2	Transitional	282	13.97
Fid_4L_17	2	Transitional	292	8.49
Fid_4L_27	3	Transitional	302	7.43
Fid_4L_37	3	Transitional	312	7.89
Fid_4L_47	3	Transitional	322	5.92
Fid_4L_57	3	Transitional	332	14.36
Fid_4L_67	3	Late-Glacial	342	3.50
Fid_4L_77	4	Late-Glacial	352	4.79
Fid_4L_87	4	Late-Glacial	362	3.17
Fid_4L_97	4	Late-Glacial	372	2.66
Fid_5L_12	4	Full-Glacial	383	4.03
Fid_5L_32	4	Full-Glacial	403	2.48
Fid_5L_52	4	Full-Glacial	423	4.63
Fid_5L_72	4	Full-Glacial	443	3.79
Fid_5L_92	4	Full-Glacial	463	3.69

(table continues)

Sample	Lith. Unit	Phase	Depth (cm)	Organic Matter Content
Fid_6L_21	4	Full-Glacial	489	1.92
Fid_6L_41	4	Full-Glacial	509	2.34
Fid_6L_61	4	Full-Glacial	529	4.03
Fid_6L_81	4	Full-Glacial	549	3.52
Fid_7L_02	4	Full-Glacial	569	2.73
Fid_7L_22	4	Full-Glacial	589	2.37
Fid_7L_32	4	Full-Glacial	599	2.31
Fid_7L_42	4	Full-Glacial	609	3.78
Fid_7L_62	4	Full-Glacial	629	3.38
Fid_7L_82	4	Full-Glacial	649	3.83
Fid_8L_27	4	Full-Glacial	670	2.15
Fid_8L_47	4	Full-Glacial	690	2.45
Fid_8L_67	4	Full-Glacial	710	3.44
Fid_8L_87	4	Full-Glacial	730	3.47
Fid_9L_09	4	Full-Glacial	750	3.49
Fid_9L_29	4	Full-Glacial	770	3.39
Fid_9L_49	4	Full-Glacial	790	3.49
Fid_9L_69	4	Full-Glacial	810	3.43
Fid_9L_89	4	Full-Glacial	830	3.34
Fid_9L_95	4	Full-Glacial	836	3.43
Fid_9L_97	5	Full-Glacial	838	3.36
Fid_10L_03	5	Full-Glacial	841	2.62
Fid_10L_05	5	Full-Glacial	843	1.71
Fid_10L_07	5	Full-Glacial	845	1.34

Louis Lake Organic Matter Contents

Sample	Lith. Unit	Phase	Depth (cm)	Organic Matter Content
Lou_1L_70	1	Post-Glacial	7	15.46
Lou_1L_80	1	Post-Glacial	17	14.53
Lou_2L_10	1	Post-Glacial	37	13.19
Lou_2L_20	1	Post-Glacial	47	14.10
Lou_2L_30	1	Post-Glacial	57	14.79
Lou_2L_50	1	Post-Glacial	77	12.83
Lou_2L_60	1	Post-Glacial	87	15.55
Lou_3L_10	1	Post-Glacial	132	13.87
Lou_3L_20	1	Post-Glacial	142	14.69
Lou_3L_50	1	Post-Glacial	172	17.85
Lou_3L_60	1	Post-Glacial	182	15.81
Lou_3L_70	1	Post-Glacial	192	20.71
Lou_3L_80	1	Post-Glacial	202	22.49
Lou_3L_90	1	Post-Glacial	212	21.04
Lou_4L_02	1	Post-Glacial	222	18.58
Lou_4L_12	1	Post-Glacial	232	22.83
Lou_4L_22	1	Post-Glacial	242	19.82
Lou_4L_42	1	Transitional	262	25.27
Lou_4L_52	1	Transitional	272	24.95
Lou_4L_62	1	Transitional	282	21.60
Lou_4L_72	1	Transitional	292	19.25
Lou_4L_82	2	Transitional	302	16.42
Lou_4L_92	2	Transitional	312	14.30
Lou_4L_102	2	Transitional	322	13.64
Lou_5L_11	2	Late-Glacial	332	10.80
Lou_5L_21	2	Late-Glacial	342	12.27
Lou_5L_31	3	Late-Glacial	352	8.77
Lou_5L_41	3	Late-Glacial	362	8.36
Lou_5L_51	3	Late-Glacial	372	3.98
Lou_5L_61	3	Full-Glacial	382	4.06
Lou_5L_71	3	Full-Glacial	392	4.16
Lou_5L_81	3	Full-Glacial	402	4.19
Lou_5L_91	3	Full-Glacial	412	3.76
Lou_6L_09	3	Full-Glacial	422	2.71
Lou_6L_29	4	Full-Glacial	442	4.56
Lou_6L_49	4	Full-Glacial	462	3.39
Lou_6L_69	4	Full-Glacial	482	3.40
Lou_6L_89	4	Full-Glacial	502	3.41

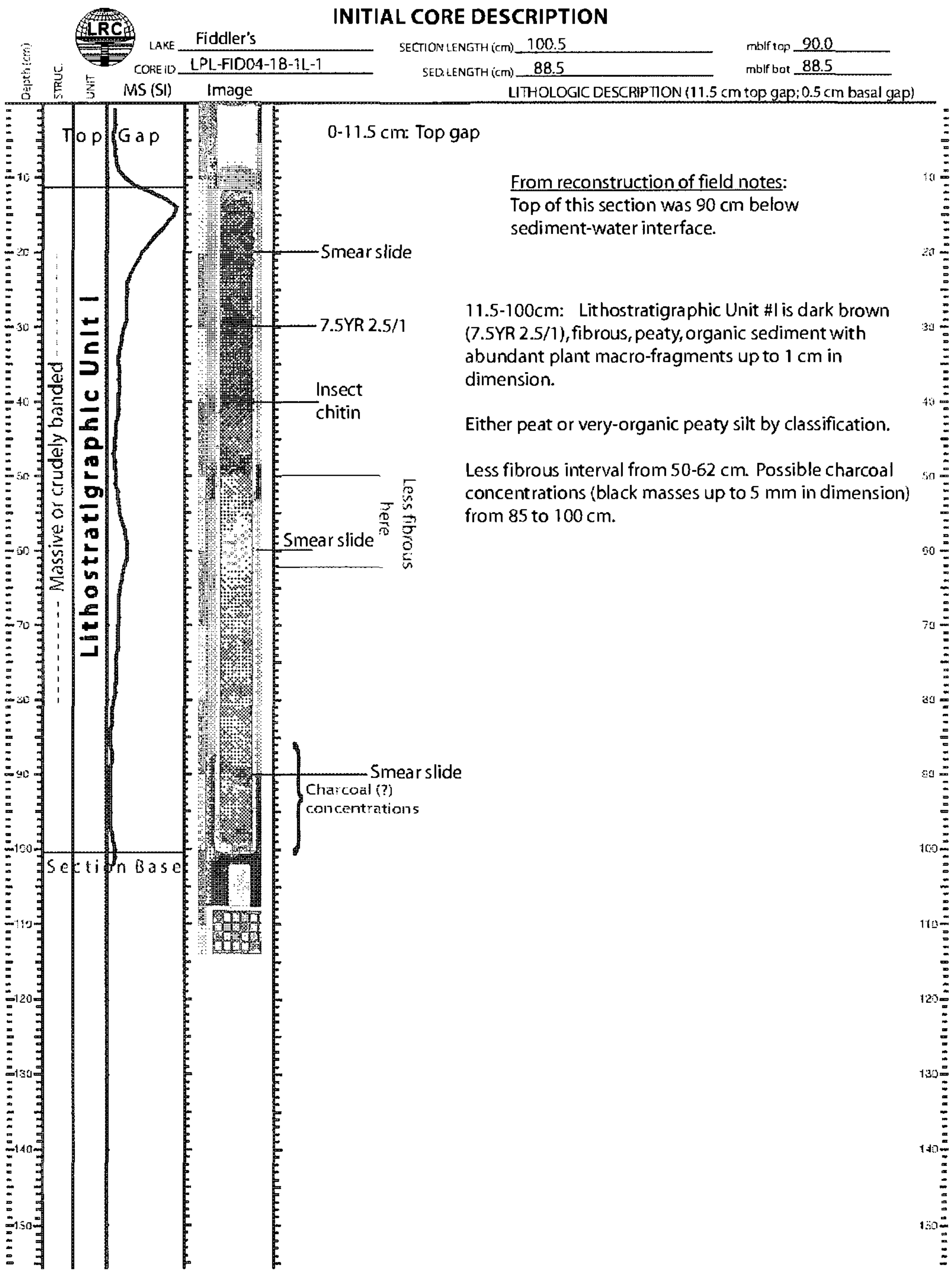
(table continues)

Sample	Lith. Unit	Phase	Depth (cm)	Organic Matter Content
Lou_7L_13	4	Full-Glacial	522	3.07
Lou_7L_33	4	Full-Glacial	542	3.25
Lou_7L_53	4	Full-Glacial	562	3.69
Lou_7L_73	4	Full-Glacial	582	3.15
Lou_7L_93	4	Full-Glacial	602	3.03
Lou_8L_59	4	Full-Glacial	652	4.07
Lou_8L_79	4	Full-Glacial	672	3.25
Lou_8L_99	4	Full-Glacial	692	3.85
Lou_9L_30	4	Full-Glacial	715	5.75
Lou_9L_50	4	Full-Glacial	735	3.72
Lou_9L_70	4	Full-Glacial	755	2.76
Lou_9L_90	4	Full-Glacial	775	4.24
Lou_10L_26	4	Full-Glacial	793	3.83
Lou_10L_46	4	Full-Glacial	813	2.51
Lou_10L_66	4	Full-Glacial	833	2.76
Lou_10L_86	4	Full-Glacial	853	3.56
Lou_11L_31	4	Full-Glacial	873	3.27
Lou_11L_51	4	Full-Glacial	893	3.49
Lou_11L_71	4	Full-Glacial	913	3.43
Lou_11L_91	4	Full-Glacial	933	3.03

APPENDIX D

INITIAL CORE DESCRIPTION SHEETS

Fiddlers Lake

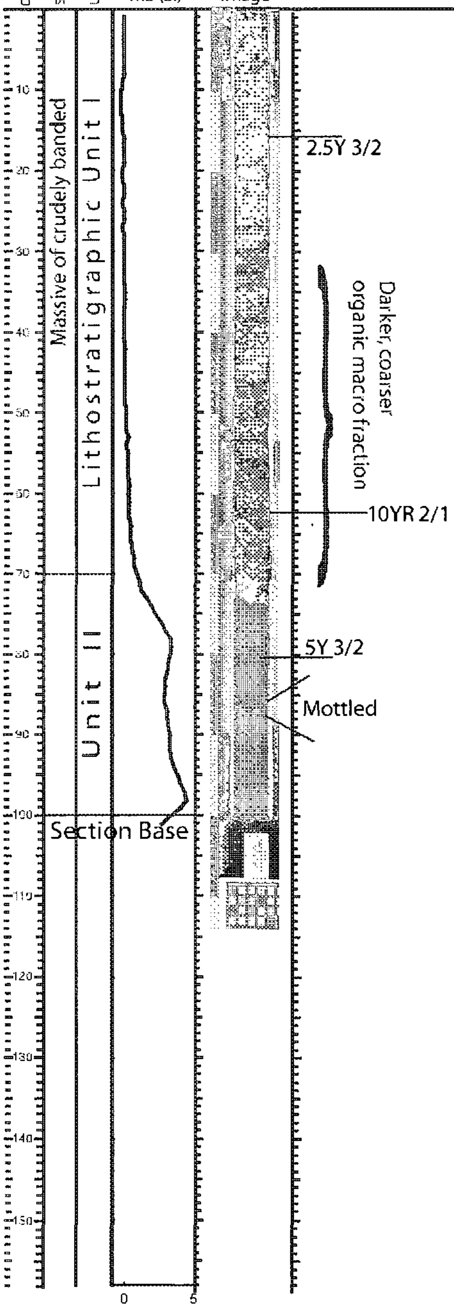


INITIAL CORE DESCRIPTION

LAKE Fiddler's | SECTION LENGTH (cm) ###.# | mblf top ###.#

CORE ID LPL-FID04-1A-3L-1 | SED. LENGTH (cm) ###.# | mblf bot ###.#

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



* From reconstruction based on field notes -- This section is approximately continuous with LPL-FID04-1B-1L-1

0-70 cm: Continuation of lithostratigraphic Unit #1 from previous section.

Dark grayish brown to black, fibrous, peaty. Peat or very organic-rich silt, probably peat by classification. Basal 30 cm of this unitis darker and coarser (in orgainc macro fraction).

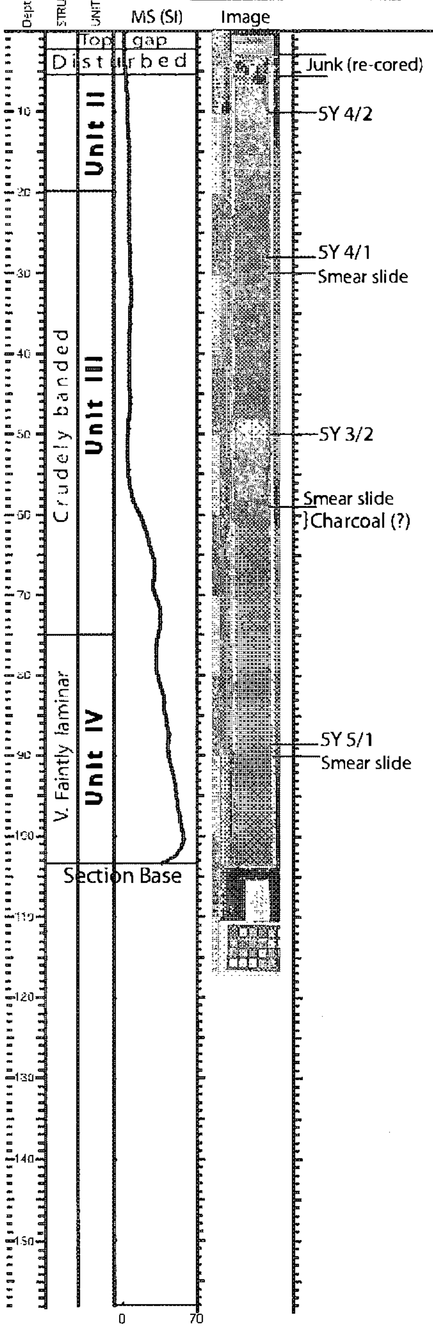
Distinct downward contact to Unit II, dark olive gray, faintly laminated silt with scattered pebbles (drop-stones) to 2 mm. Mottled, possible bioturbation at 84-87 cm. 70-74 cm silty, non-fibrous but dark; evidently staining from humic compounds in Unit I (?).

Micaceous flecking prominent on split core face.

INITIAL CORE DESCRIPTION

LAKE Fiddler's — SECTION LENGTH (cm) 103.5 — mblf top 290.0

CORE ID LPL-FID04-1A-4L-1 — SED. LENGTH (cm) 101.2 — mblf bot 391.2



LITHOLOGIC DESCRIPTION (2.3 cm top gap)

0-2.3 cm Top gap

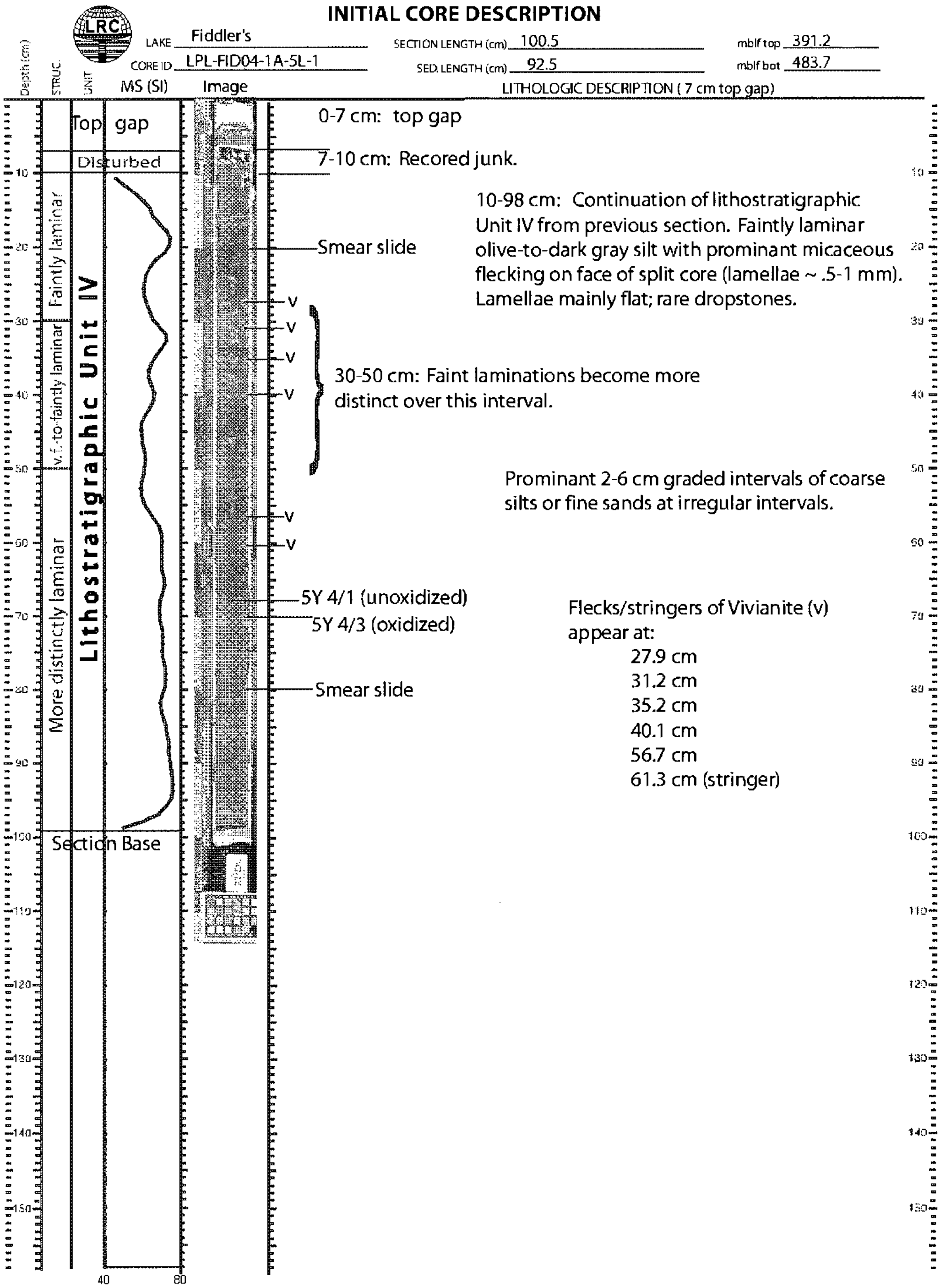
2.3-5.5 cm: Recore - disturbed

5.5-20 cm: Continuation of lithostratigraphic Unit II from previous section. Faintly laminated olive gray silt with prominent micaceous flecking on split core face.

Distinct downward contact with lithostratigraphic unit III. Unit III is characterized by less of (or reduced visibility of) micaceous flecking and by prominant orange plant macrofragments, mostly matrix-supported in the silt. 0.3 mm to 1 cm characteristic scale, compressed parallel to deposition.

48 to 61 cm is noteably darker, higher concentration of plant fragments. Black flecking from 59-61 cm, possible charcoal concentration.

Distinct downward contact with Unit IV. Unit IV remains grey or olive gray silt, very faintly laminar-to-massive, lacking the plant fragments characteristic of Unit III above.


INITIAL CORE DESCRIPTION
LRC
LAKE Fiddler's
CORE ID LPL-FID04-1A-5L-1
SECTION LENGTH (cm) 100.5
SED. LENGTH (cm) 92.5
mblf top 391.2
mblf bot 483.7
Depth (cm)
STRUC.
UNIT
MS (SI)
Image
LITHOLOGIC DESCRIPTION (7 cm top gap)
Top gap
Disturbed
Faintly laminar
v.f.-to-faintly laminar
More distinctly laminar
Lithostratigraphic Unit IV
Section Base
0-7 cm: top gap
7-10 cm: Recored junk.
10-98 cm: Continuation of lithostratigraphic Unit IV from previous section. Faintly laminar olive-to-dark gray silt with prominant micaceous flecking on face of split core (lamellae ~ .5-1 mm). Lamellae mainly flat; rare dropstones.
Smear slide
30-50 cm: Faint laminations become more distinct over this interval.
Prominant 2-6 cm graded intervals of coarse silts or fine sands at irregular intervals.
5Y 4/1 (unoxidized)
5Y 4/3 (oxidized)
Flecks/stringers of Vivianite (v) appear at:
27.9 cm
31.2 cm
35.2 cm
40.1 cm
56.7 cm
61.3 cm (stringer)
Smear slide
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
40
80

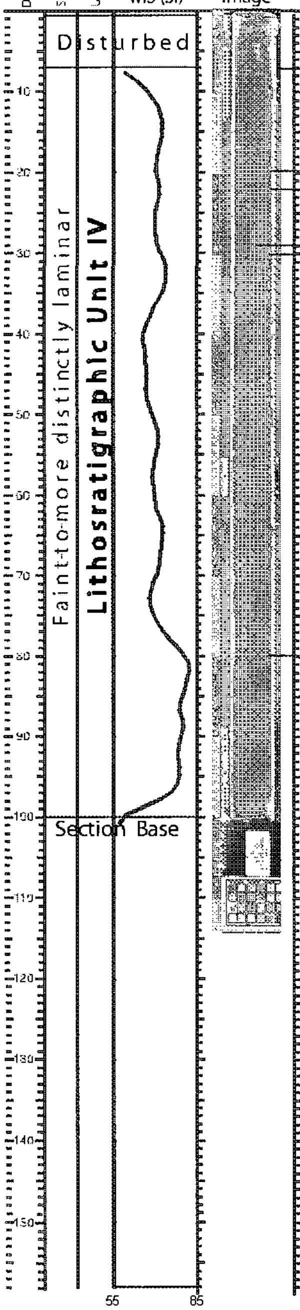
INITIAL CORE DESCRIPTION

LRC

LAKE Fiddler's | SECTION LENGTH (cm) 100.2 | mblf top 483.7

CORE ID LPL-FID04-1A-6L-1 | SED. LENGTH (cm) 98.9 | mblf bot 582.6

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION (0.5 cm top gap)



0.5 cm top gap

0.5-7 cm: disturbed

Smear slide

Grain of med/coarse sand (22.1 cm)

Reduced (5Y 4/1)

Oxidized (5Y 4/3)

7-99.4 cm: Continuation of lithostratigraphic Unit IV. Faintly laminar olive-to-dark gray silt w/ prominant micaceous flecking on face of split core. Lamellae thicknesses vary from 0.5-to-2 mm.

Laminations remain faint-to-distinct throughout section. The prominent 2-6 mm graded intervals of coarse silt and/or fine sand appear in very faint packages within intervals of 3-5 cm (this may not be demonstrated by the instrumental records (visual trick?).

No Vivianite observed in this core section.

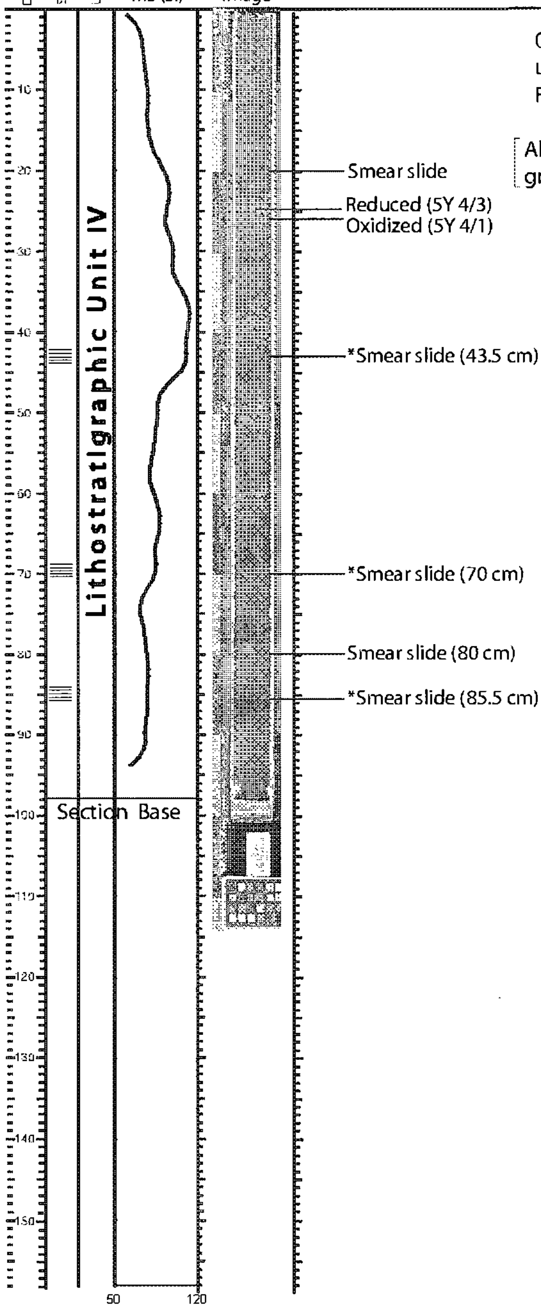
Smear slide

INITIAL CORE DESCRIPTION

LAKE Fiddler's SECTION LENGTH (cm) 100.5 mblf top 582.6

CORE ID LPL-FID04-1A-7L-1 SED. LENGTH (cm) 97.8 mblf bot 680.4

Depth (cm) STRUC. UNIT MS (SI) Image LITHOLOGIC DESCRIPTION



0 - 97.8 cm: Continuation of lithostratigraphic unit IV. Description same as in drives 4, 5, & 6. Faint-to-distinctly laminar.

[All descriptions of laminations & coarser graded intervals = same as above core sections]

No Vivianite observed in this section.

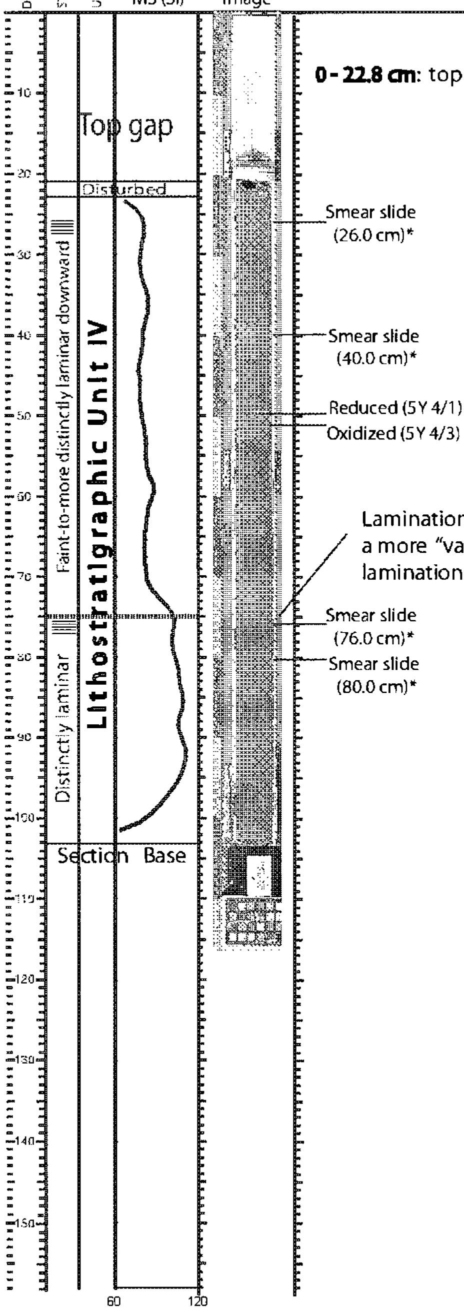
Smear slides for general observation at 20 cm & 80 cm.

* Smear slides of coarser graded packages:
43.5 cm
70.0 cm
85.5 cm

INITIAL CORE DESCRIPTION

LAKE Fiddler's
CORE ID LPL-FID04-1A-8L-1
SECTION LENGTH (cm) 103.3
SED. LENGTH (cm) 82.5
mblf top 680.4
mblf bot 762.9

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION (21 cm top gap)



0 - 22.8 cm: top gap

22.8 - 103.3 cm: Continuation of Lithostratigraphic Unit IV from sections 4-5-6-7.
All descriptions = same.

Laminations begin to appear more distinct & begin to take on a more "varved" appearance with lighter/darker alternating laminations (~1 mm).

General smear slides: 20 & 80 cm

Smear slides of coarser graded intervals & laminations* at 26.0 &76.0 cm.

INITIAL CORE DESCRIPTION

LRC

LAKE Fiddler's | SECTION LENGTH (cm) 100.3 | mblf top 762.9

CORE ID LPL-FID04-1A-9L-1 | SED. LENGTH (cm) 94.0 | mblf bot 856.9

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION (5 cm top gap)

Top gap

Possibly disturbed

Moderately-distinct to distinct laminations (varves?)

Lithostratigraphic Unit IV

V

Section Base

0-5 cm: top gap

5-8 cm: possibly disturbed

8-96.7 cm: Continuation of Lithostratigraphic Unit IV from previous sections. Same characteristics as described in previous sections EXCEPT:
Laminations appear more distinctly "varve-like" with separate 1 mm laminations of alternating lighter/darker colors.

Smear slide (20 cm)

Oxidized (5Y 4/3)
Reduced (5Y 4/1)

} Laminations VERY distinct
(smear slides taken at 54.5 & 55.0 cm)

Smear slide of coarse graded interval (56 cm)

Smear slide (80 cm)

Lithostratigraphic Unit V: Very coarse-to-fine sands. One coarse graded interval occurs at 96.7 cm and is separated from a second interval at 97.6 cm by silts. Second cgi then includes coarse-medium sands to the Section Base at 99.0 cm.

Smear slide (98.5 cm)

10 20 30 40 50 60 70 80 90 100 110 120 130 140 150

40 160

INITIAL CORE DESCRIPTION

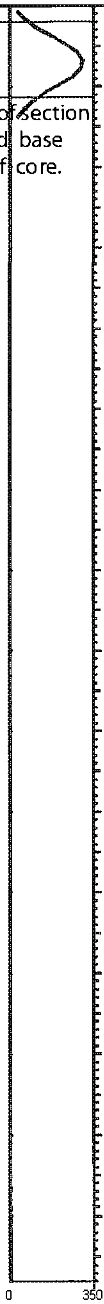
LAKE Fiddler's — SECTION LENGTH (cm) 14.0 cm — mblf top 856.9 cm

CORE ID LPL-FID04-1A-10L-1 — SED. LENGTH (cm) 9.5 cm — mblf bot 866.4 cm

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION (2 cm top gap)

Unit V

Base of section and base of core.



0-2 cm: top gap

Smear slide (7.0 cm)

Unoxidized silts (5Y 4/1)
Oxidized sands (2.5Y 4/4)

2-11.5 cm: Continuation of <u>Lithostratigraphic Unit V</u> as described in Section 9. Fine-to-coarse sands and small gravels. this is either the top of an eroded weathering zone or coarse outwash from the lateral moraine that dams the lake to the south.

NOTE: This section is contained in a full-length tube.

10 20 30 40 50 60 70 80 90 100 110 120 130 140 150

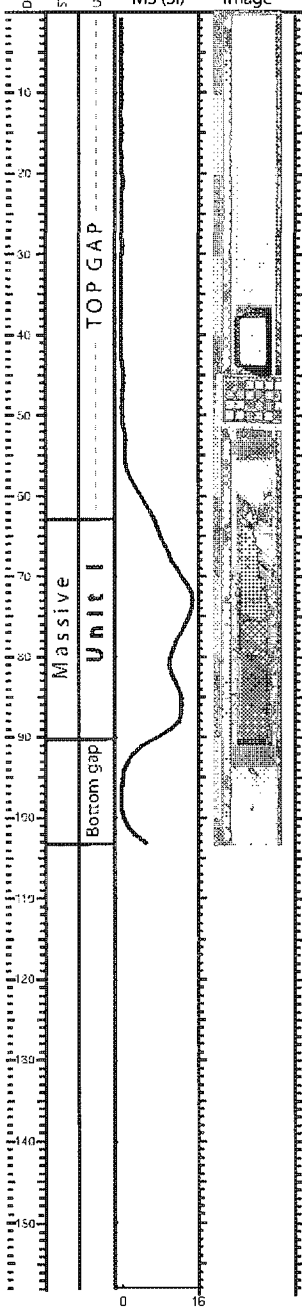
Louis Lake

INITIAL CORE DESCRIPTION

LAKE Louis — SECTION LENGTH (cm) 103 — mblf top 0

CORE ID LPL-LOU04-1A-1L-1 — SED. LENGTH (cm) 27.5 — mblf bot 27.5

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



63 - 95cm: Lithostratigraphic Unit #1. Dark Grayish Brown* (oxidized outer core) to Black (inner reduced material) massive organic silt (?) with scattered grains of sand (up to coarse) and abundant micaceous flecking (< 0.5mm) on split core face.

Oxidized: 10YR3/2
Reduced: 2.5Y2.5/1

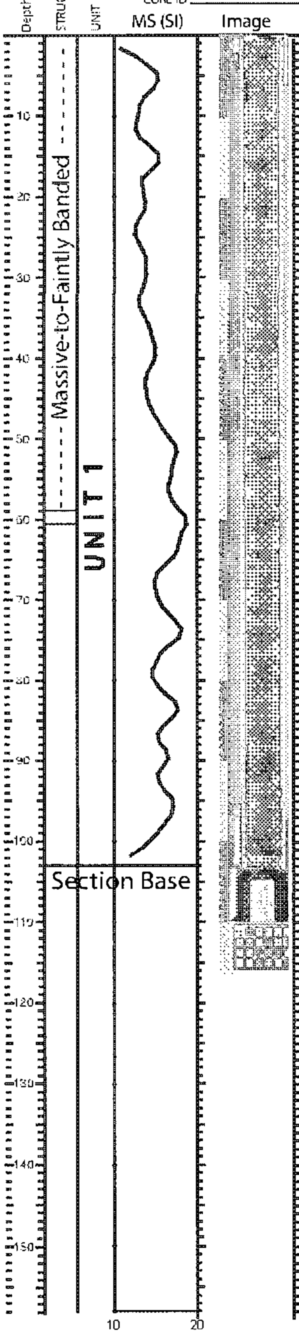
*Narrative color descriptions correspond to Munsell colors.

INITIAL CORE DESCRIPTION

LRC

LAKE Louis | SECTION LENGTH (cm) 103.3 | mblf top 27.5

CORE ID LPL-LOU04-1A-2L-1 | SED. LENGTH (cm) 103.3 | mblf bot 130.8



LITHOLOGIC DESCRIPTION

0 - 103.3 cm: Continuation of lithostratigraphic Unit #1 from previous section. Massive-to-faintly banded black-to-Dark Orange-Brown sandy, organic silt with occassional limonitic semi-indurated bands. Abundant micaceous flaking on core face. Nodular or semi-indurated interval at 60 - 61cm is as 1mm aggregated nodules.

Oxidized: 2.5Y3/1
Reduced: 2.5Y2.5/1

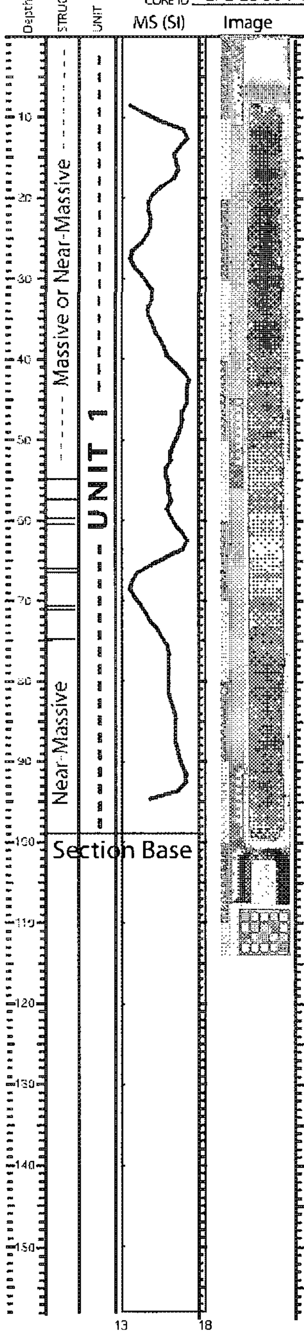
Orange band: 10YR3/3

INITIAL CORE DESCRIPTION

LAKE Louis | SECTION LENGTH (cm) 100 | mblf top 130.8

CORE ID LPL-LOU04-1A-3L-1 | SED. LENGTH (cm) 91.5 | mblf bot 222.3

LITHOLOGIC DESCRIPTION



8 - 99.5cm: Continuation of lithostratigraphic Unit #1 from previous section. Massive to faintly-banded Black to V. Dark Reddish-Brown organic silt. Less sand than abofe? Banding more distinct from 55-75cm. Abundant micaceous flecking on split core face.

Oxidized: 2.5Y2.5/1
Reduced: 7.5YR3/1

----- 5 cm bottom gap.

INITIAL CORE DESCRIPTION

LRC

LAKE Louis

CORE ID LPL-LOU04-1A-4L-1

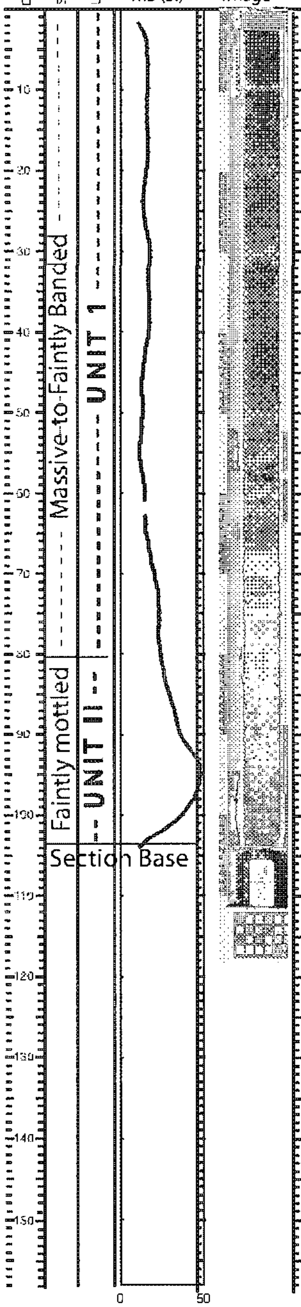
SECTION LENGTH (cm) 103.5

SED. LENGTH (cm) 101.5

mblf top 222.3

mblf bot 323.8

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



2 cm top gap.

2 - 80 cm: Continuation of Lithostratigraphic Unit I from previous section. Massive to faintly banded Black to Dark Orange-Brown organic silt with abundant micaceous flecks on split core face.

Micaceous flecking less abundant or less visible downward toward gradational contact with Unit II.

Oxidized: 10YR3/2
Reduced: 10YR2/1

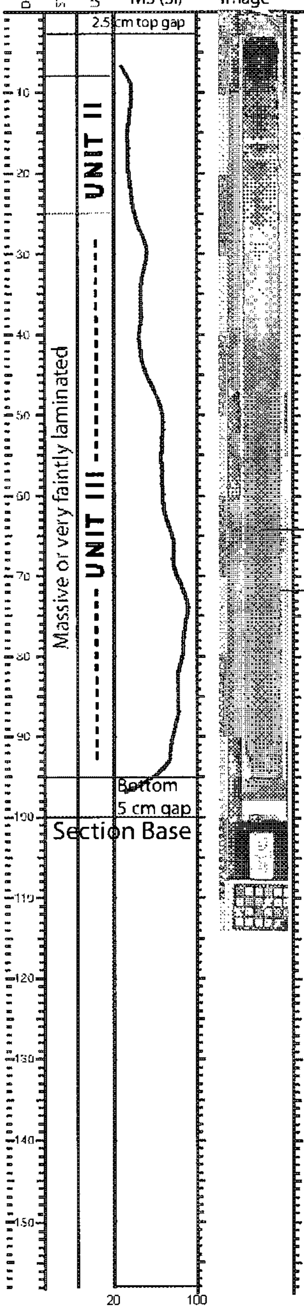
Unit II defined as beginning with first thin stringer of coarse, black flecking (charcoal?) occurring as discontinuous 2-3 mm-thick bands.

General character of surrounding sediment as in Unit I, except for faint quasi-planar mottled dark silt, rare scattered sand. Micaceous flecking less prominent than Unit I.

INITIAL CORE DESCRIPTION

LAKE Louis
CORE ID LPL-LOU04-1A-5L-1
SECTION LENGTH (cm) 100
SED. LENGTH (cm) 92.5
mblf top 323.8
mblf bot 416.3

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



2.5 - 25 cm: Continuation of lithostratigraphic Unit II from section above. Upper 5.5 cm possibly disturbed by coring.

------- Clay band (3mm)

Charcoal (?) bands diminishing downward toward gradational and rather arbitrary contact with Unit III.

------ 2 mm 'drop-stone'

25 - 95 cm: Dark gray (reduced) to olive brown silty clay or clayey silt, speckled with occasional sand grains and with small nodules and thin stringers of Vivianite. Rate coarse sand - fine pebble drop-stone.

Vivianite abundance increases downward.

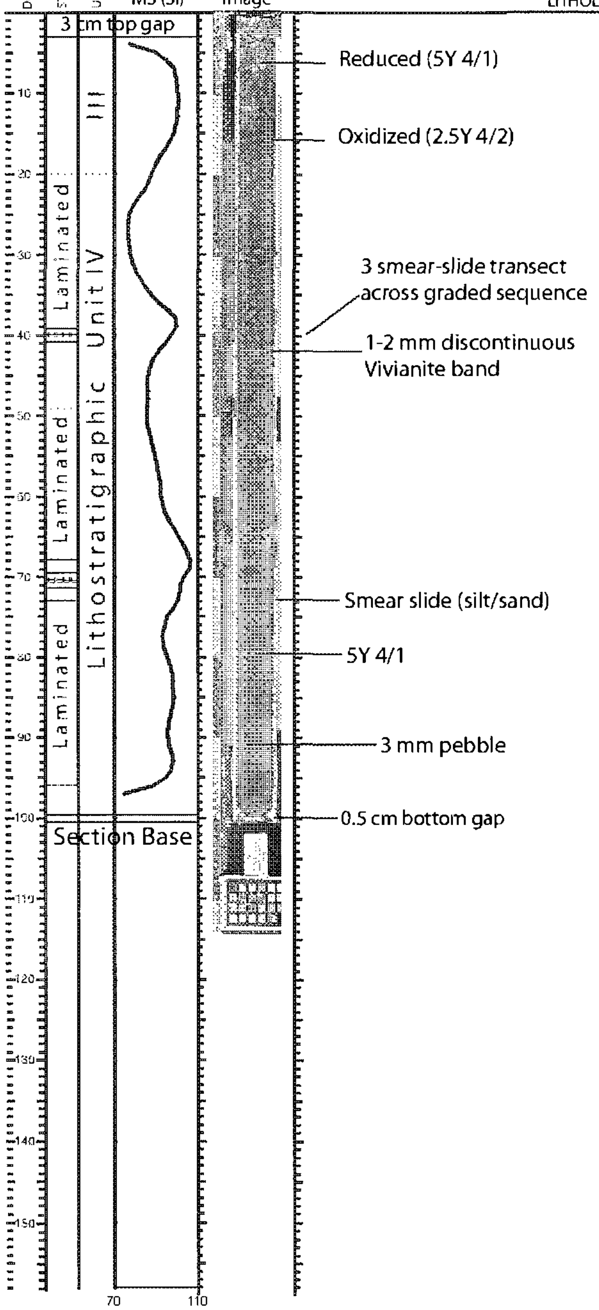
Core center (reduced) 2.5Y 4/1

Outer core (oxidized) 2.5Y 4/3

INITIAL CORE DESCRIPTION

LAKE Louis
CORE ID LPL-LOU04-1A-6L-1
SECTION LENGTH (cm) 100.2
SED. LENGTH (cm) 96.7
mblf top 416.3
mblf bot 513.0

Depth (cm) | STRUC. | UNIT | MS (SI) | Image | LITHOLOGIC DESCRIPTION



3 - 20 cm: Continuation of lithostratigraphic unit III from previous section. Massive-to-very faintly laminated dark gray (red) to olive brown (ox) clayed silt or silty clay.

Downward gradational transition to Unit IV is defined by increasingly well-preserved lamellae. 0.5-1.0 mm lamellae in light gray (finer) and darker (coarser) couplets.

Vivianite ONLY in the obvious band.

Prominent ~1 cm graded packages at 40-41 and 70-71 cm. Prominant nodular Vivianite band at 41.3 cm. Vivianite occurs ONLY in the obvious sand.
1-5 mm coarse silts or fine sands at irregular intervals.

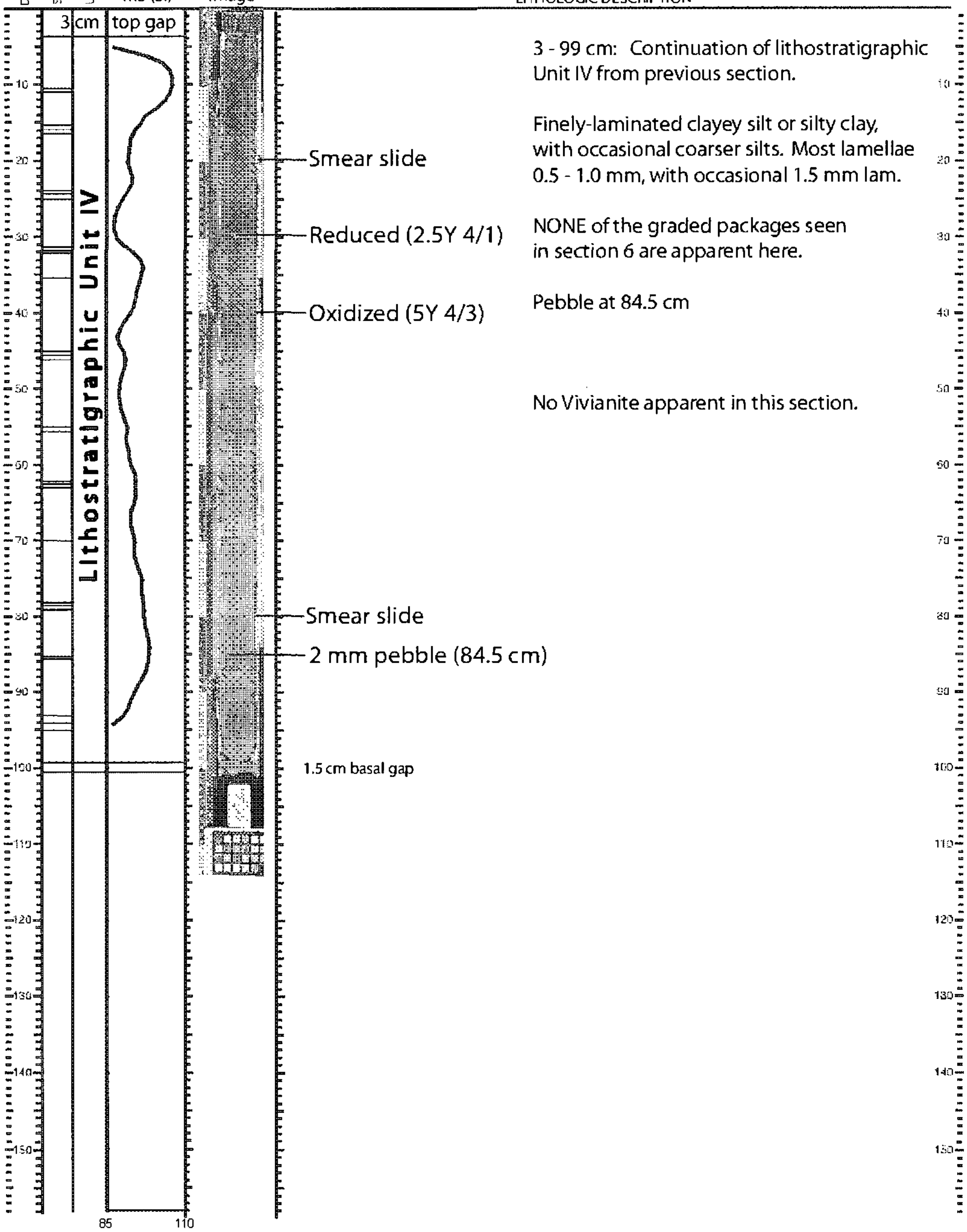
Lamellae flat or very slightly wavey.

Rare drop-stone(s)

INITIAL CORE DESCRIPTION

LAKE Louis | SECTION LENGTH (cm) 100.5 | mblf top 513.0

CORE ID LPL-LOU04-1A-7L-1 | SED. LENGTH (cm) 96.0 | mblf bot 609.0



LITHOLOGIC DESCRIPTION

3 - 99 cm: Continuation of lithostratigraphic Unit IV from previous section.

Finely-laminated clayey silt or silty clay, with occasional coarser silts. Most lamellae 0.5 - 1.0 mm, with occasional 1.5 mm lam.

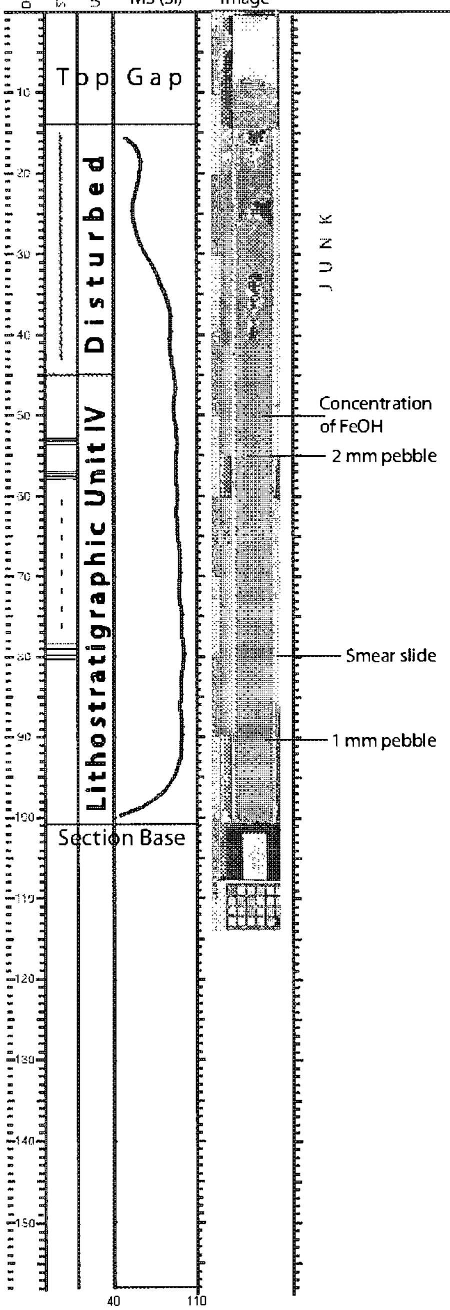
NONE of the graded packages seen in section 6 are apparent here.

Pebble at 84.5 cm

No Vivianite apparent in this section.

INITIAL CORE DESCRIPTION

LAKE Louis
CORE ID LPL-LOU04-1A-8L-1
SECTION LENGTH (cm) 100.0
SED. LENGTH (cm) 86.0
mblf top 609.0
mblf bot 695.0



LITHOLOGIC DESCRIPTION

0-14 cm top gap.

14-45 cm disturbed material (re-core).

At about 45 cm the structure of Unit IV becomes visible again. Above 45 cm, interpreted as coring artifact, slumped matrial including blocks of apparent Unit I or II material recored.

45-100 cm: Continuation of Unit IV from previous section. Finely laminated dark gray (5Y4/1) clayey silt or silty clay with occasional fine sand or coarse silt stringers, and scattered drop-pebbles 1-2mm in dimension.

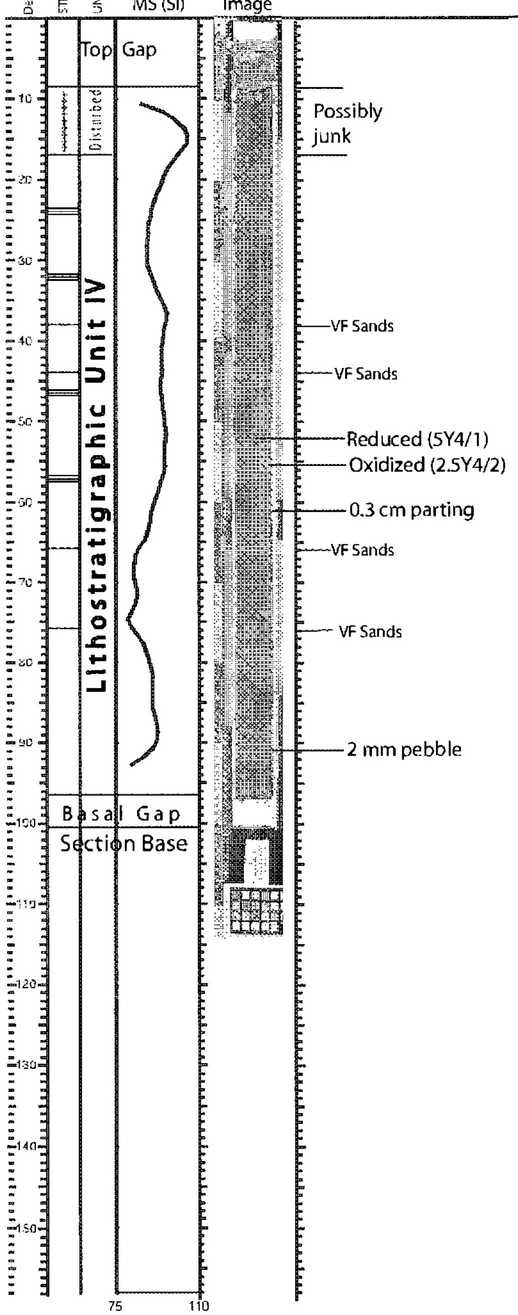
This section is slightly-to-moderately disturbed (pinched and distorted lamelllae) but clearly intact.

Lamellae 0.5-1.0 mm, occasionally thicker.
The cm-scale graded packages seen in upper section of this unit are absent in this section.

No Vivianite apparent in this section.

INITIAL CORE DESCRIPTION

LAKE Louis
CORE ID LPL-LOU04-1A-9L-1
SECTION LENGTH (cm) 100.5
SED. LENGTH (cm) 87.7
mblf top 695.0
mblf bot 782.7



LITHOLOGIC DESCRIPTION (8.5cm top gap; 4 cm basal gap; 0.3 cm interior gap)

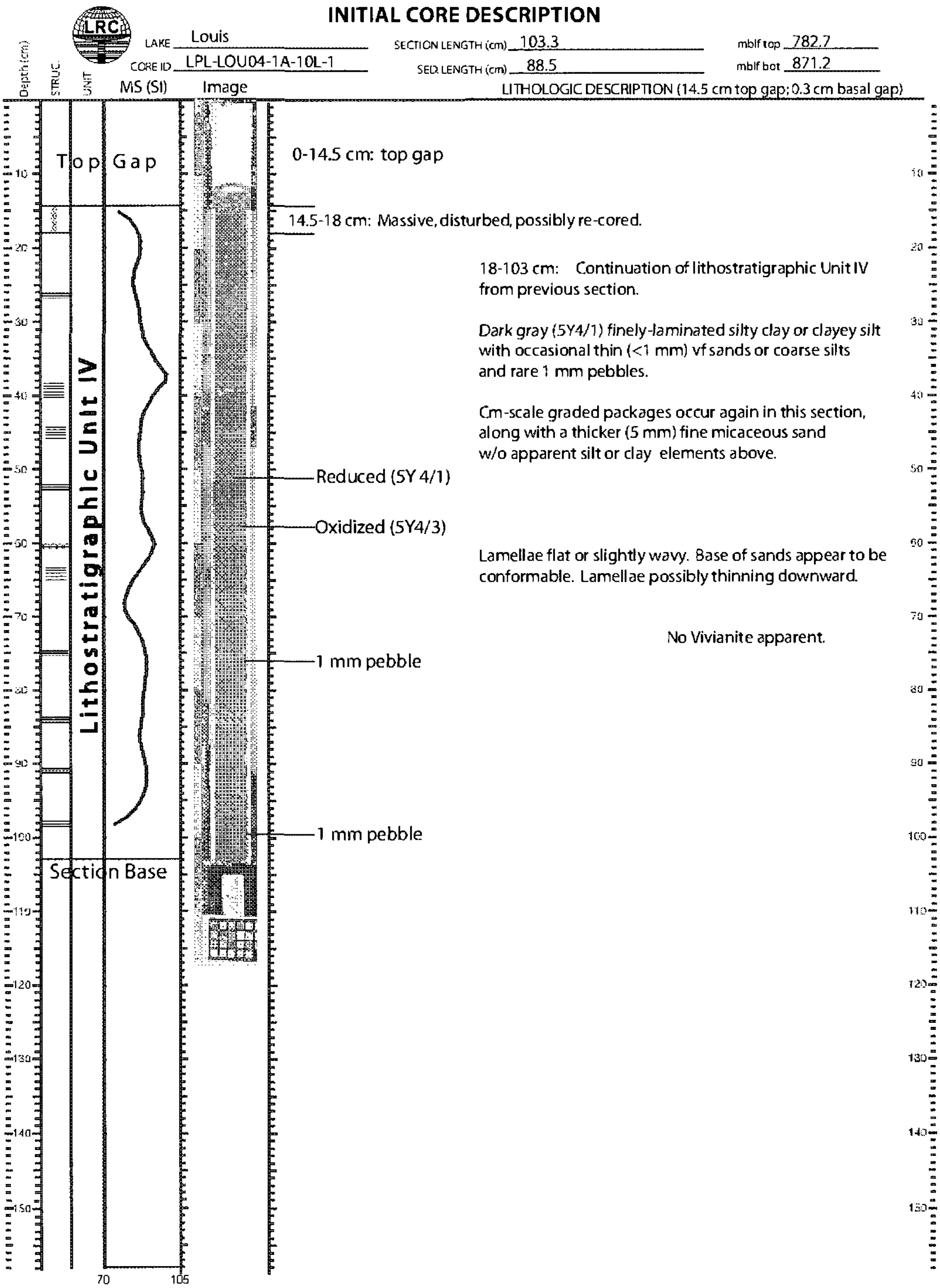
0-8 cm: Top gap

8-17 cm: Massive, disturbed and possible re-core.

17-96.5 cm: Continuation of lithostratigraphic Unit IV from previous section.
Finely laminated clayey silt or silty clay with fine sands ~ 1mm thick. Apparently more common than in Unit IV above. Lamellae flat or nearly flat occassional thin (<1 mm) light gray clay (?) lamellae, rare 1-2 mm pebbles.

~1-2 cm-thick graded packages are absent.

No Vivianite apparent.

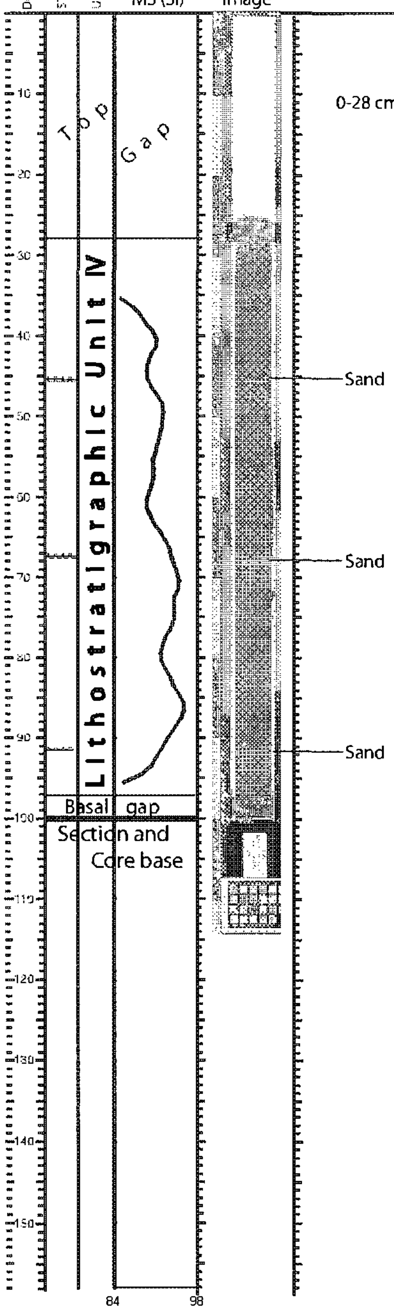


INITIAL CORE DESCRIPTION
LRC
LAKE Louis
CORE ID LPL-LOU04-1A-10L-1
SECTION LENGTH (cm) 103.3
SED. LENGTH (cm) 88.5
mblf top 782.7
mblf bot 871.2
Depth (cm)
STRUC.
UNIT
MS (SI)
Image
LITHOLOGIC DESCRIPTION (14.5 cm top gap; 0.3 cm basal gap)
Top Gap
Lithostratigraphic Unit IV
Section Base
70
105
0-14.5 cm: top gap
14.5-18 cm: Massive, disturbed, possibly re-cored.
18-103 cm: Continuation of lithostratigraphic Unit IV from previous section.
Dark gray (5Y4/1) finely-laminated silty clay or clayey silt with occasional thin (<1 mm) vf sands or coarse silts and rare 1 mm pebbles.
Cm-scale graded packages occur again in this section, along with a thicker (5 mm) fine micaceous sand w/o apparent silt or clay elements above.
Reduced (5Y 4/1)
Oxidized (5Y4/3)
Lamellae flat or slightly wavy. Base of sands appear to be conformable. Lamellae possibly thinning downward.
No Vivianite apparent.
1 mm pebble
1 mm pebble

INITIAL CORE DESCRIPTION

LAKE Louis
CORE ID LPL-LOU04-1A-11L-1
SECTION LENGTH (cm) 100.0
SED. LENGTH (cm) 68.6
mblf top 871.2
mblf bot 939.8

LITHOLOGIC DESCRIPTION (28 cm top gap; 3 cm basal gap; 0.4 cm interior partings in 3 gaps.



0-28 cm top gap.

28-97 cm: Continuation of lithostratigraphic Unit IV from previous section. *Finely to V. finely-laminated dark gray (5Y4/1)* silty clay or clayey silt with occasional ≤ 1 mm silts or fine sands and 3 prominent stringers of fine sand 1-2 mm thick at 45.5, 67.5, and 91.5 cm. These have formed partings on the core face.

Lamellae thinning downwaard to base of core. Cm-scale graded packages absent again.

Very thin, light gray clay (?) lamellae become prominent near base of section.

No Vivianite apparent.

Base of section and core base does not represent the base of lake sediment available.