WIRELINE SEDIMENTOLOGY: Resedimented Volcaniclastites

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by

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UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF SCIENCE

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WIRELINE SEDIMENTOLOGY: Resedimented Volcaniclastites

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The main focus of this thesis is to explore and develop the application of wireline logs in solving sedimentological problems, and so to further underline the importance of Wireline Sedimentology as a distinct discipline. The principal logs used are Formation MicroScanner (FMS) images, together with dipmeter-microresistivity, gamma ray and geochemical plots, taken during ODP Leg 129 in the Pigafetta and E. Mariana Basins, W. Central Pacific.

Seven resedimented volcaniclastic facies including slumps, debrites, and turbidites are recognised within thick (115-221 m) but poorly recovered (4-68%) Cretaceous and Miocene-Pliocene volcaniclastic units. A combination of wireline logs calibrated or correlated with recovered intervals and with known signatures, can be used to delineate facies in poorly recovered and badly disturbed coring intervals and hence to construct a complete borehole record of FMS image descriptions (FIDs). From these, it is possible to identify macro-, meso- and microsequences (>100, 10-100 & <10m thick respectively) of turbidite facies on the basis of bed-thickness trends. Whereas the macro- and mesosequences are a response to allocyclic volcano-tectonic controls, both oscillation and saw-tooth microsequences reflect autocyclic controls, including turbidite compensation effects. A new model for the sedimentary successions developed around volcanic archipelagoes and within mid-ocean basins is presented, taking into account the types of sequence observed and their likely controls.

Since FMS images formed the basis of all interpretations outlined above, a scheme defining the context of FMS image data sequences is proposed, that includes: physical, global, and local contexts. This method of approach can be used in part or in full to document even very fine scale sedimentological features and to interpret their origin (e.g., bed pinch-out direction, based on cross-lamination or bioturbation).

Sequentially enhanced FMS images of highly bioturbated turbidite/hemiturbidite beds reveal six types of pattern in terms of image-mottles that can be correlated with the possible ichno-toponomic features observed on recovered core pieces and with known deep marine ichnogenera. Moreover, a slightly modified nomenclature of turbiditic bioturbation based on FMS image studies is proposed, that includes inter-turbidite, post-turbidite, and intra-turbidite bioturbation.

Further research may enhance the applications of wireline logs, specifically of FMS images, to uncover the enigma of core-orientation and core-loss in boreholes and allow even more detailed resolution of sedimentological features.

ACKNOWLEDGEMENT

I owe a great debt of gratitude and respect to my supervisor, Dr Dorrik Stow, for his constant help, guidance and friendship throughout this piece of research. My sincere gratitude to my advisory board members: Prof. J.W. Murray, and Dr C.A. Boulter, for their useful suggestions and kind attitudes.

Initial thanks to NERC, UK , for its kind support for my participation in the in-cruise and post-cruise programmes of the ODP Leg 129. My sincere gratitude to my supervisor Dr Stow and the Geology Department, Southampton University for supporting me in many ways (financial, logistical etc) in order to carry out the research smoothly. GAPS, the geological consultancy firm in London is also acknowledged for its generous offer of a temporary job during my uncertain condition of funding in 1990.

For supplying some data (e.g., core photos), my thanks to ODP, Texas A & M University staff. I would like to express my best regards and gratitude to the Borehole Research Group (especially to Robin Reynolds) in Lamont Doherty Geological Observatory of Columbia University, USA, and to the Geologists (Mr R. Cull & Mr P. Jeffery) in Schlumberger, London, for their technical as well as computational help in processing various types of wireline log data including FMS images.

Finally, my wonderful scientific colleagues and technical staff of the ODP Leg 129, with whom this piece of research first germinated; and of the Geology Department, Southampton University, with whom the said piece of research has evolved and eventually come to fruition; each of them would be in my mind, as a friend in need.

DEDICATION

In memory of my late father A. Malek; in honour of my beloved mother Latifa Begum; and in affection of Jay & Hayley.

INTRODUCTION

The idea for this research stemmed from the author's participation as shipboard sedimentologist on ODP (Ocean Drilling Program) Leg 129 to the West Central Pacific (November 1989 - January 1990).

Three sites were drilled during this leg: Sites 800 and 801 were drilled in the Pigafetta Basin and site 802 in East Mariana Basin in the West Central Pacific. The tectonic setting of the basins and location of the sites are shown in Figure 1. The regional bathymetry of the basins is shown in Figure 2 and the site summary reports prepared by the shipboard scientists are presented in Table 1 (Lancelot, Larson, et al., 1990).

The lithostratigrapies of the sites drilled are shown in Figure 3. The thick sequences of Cretaceous and Miocene-Pliocene volcaniclastic sediments encountered at these sites have been the particular focus for this research for the following reasons:

(a) relatively few studies have documented the detailed nature of deep-water resedimented volcaniclastic facies; and

(b) wireline log characterisation of volcaniclastic sediments is even more rare, and nothing has previously been published on Formation MicroScanner logs through such sediments.

(c) little was previously known about mid-plate volcanic-sedimentological evolution in this part of the Pacific Ocean.

The data collected and prepared on ODP Leg 129 offered a unique opportunity to address these areas of study.

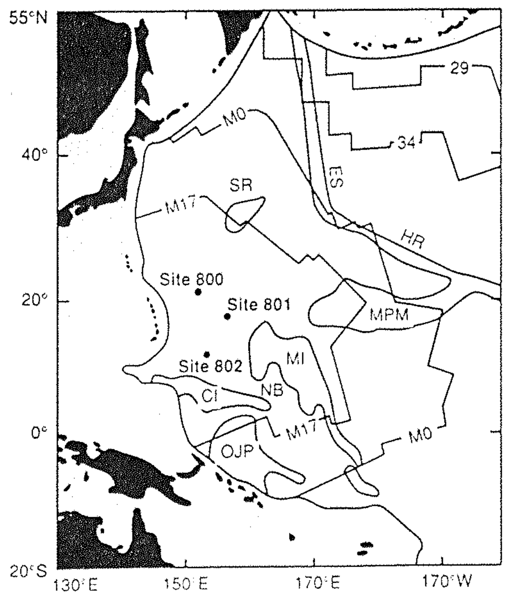

Fig 1. Location of Leg 129 sites 800, 801 and 802. Bedrock isochrons are determined from magnetic anomaly lineation mapping on the Pacific plate and superimposed on group of islands , atolls, and guyots in the Western Pacific Ocean. (feature abbreviations are as follows: Caroline Islands (CI), Ontong Java Plateau (OJP), Marshall Islands (MI), Nauru Basin (NB), Mid-Pacific Mountains (MPM), Shatsky Rise (SR), Hawaiian Ridge (HR), and Emperor Seamounts (EM). Jagged contours represent magnetic lineations and unshaded areas represent normal Pacific oceanic crust. Shaded areas represent volcanic edifices with thickened crustal sections, as well as the younger areas beyond the Pacific subduction zones).

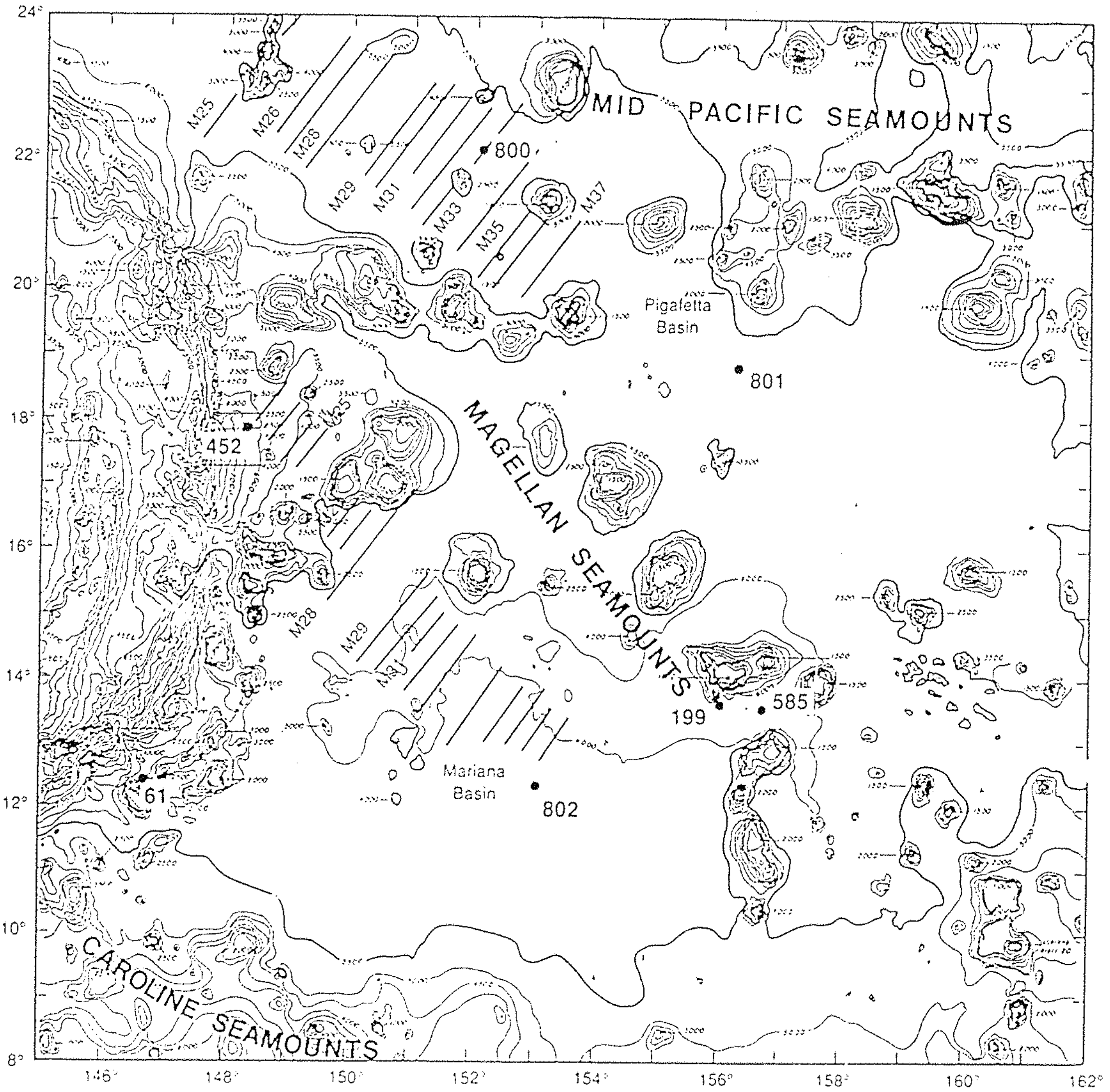

Fig 2. ODP site locations superimposed on Jurassic magnetic lineations and regional bathymetry (in metres) of the Pigafetta and East Mariana basins. Only the sites located in the deep basins of the Western Pacific are shown (from Lancelot, E., Larson, R. L., *et al.*, 1990).

I.A Statement

I.A.1 Thesis organisation

The bulk of the thesis is written as a series of six scientific papers dealing with different aspects of the study. These are prepared by sections on the scientific aims, background, and methodology. The first three papers (Papers 1, 2, 3; see paper section of this thesis) are already published. The revised version of Paper 4 is submitted to the Editor, 'Marine & Petroleum Geology', following revisions proposed by the reviewers. The initial manuscript of Paper 5 (proposed) has been submitted to the Editor, 'Sedimentology' and of Paper 6 (proposed) is being submitted to the Editor, 'Marine & Petroleum Geology'. There is also an independent concluding section (Discussion chapter).

Hole	Latitude	Longitude	Water depth (m)	Number of cores	Interval cored (m)	Recovered core (m)	Percent recovered	Interval drilled	Total penetration (m)
00A	21-55.38 N	152-19.32E	5697.0	61	544.5	152.7	28.0	.0	544.5
801A	18-38.57N	156-21.57E	5693.0	20	186.0	31.5	16.9	.0	186.0
801B	18-38.52N	156-21.58E	5693.0	44	317.2	59.2	18.7	186.0	503.2
801C	18-38.54N	156-21.59E	5685.0	12	100.6	60.6	60.2	493.7	594.3
802A	12-05.78N	153-12.62E	5980.0	62	559.8	165.0	29.5	.0	559.8
Leg TOTALS	N/A	N/A	N/A	199	1708.1	469.0	27.5	679.7	2387.8

Table 1. Ocean Drilling Program Site summary report, Leg 129 (modified from Lancelot, Larson, et al., 1990).

I.A.2 Role of authors

Three authors are involved in writing as well as preparing all the papers/manuscripts except Paper 1 and Paper 6 (see the paper section of this thesis). A.R.M. Salimullah (ARMS), the research student, is the principal author of all papers/manuscripts; Dr D.A.V. Stow (DAVS), the supervisor, is the second author of Papers 2, 3, 4, and 5; Mr R.E.S. Cull (RESC), Geologist, Schlumberger, London, is the third author of Paper 4.

The basic ideas/concepts of all the papers are largely the thoughts of the principal author (ARMS), which are enhanced as well as refined through discussions between the principal and the respective second author. The overall linguistic and scientific corrections of all the initial manuscripts, rearrangement and rewriting of abstract (3rd & 5th Papers), methodology (3rd & 5th Papers), and input into the discussion and conclusion sections

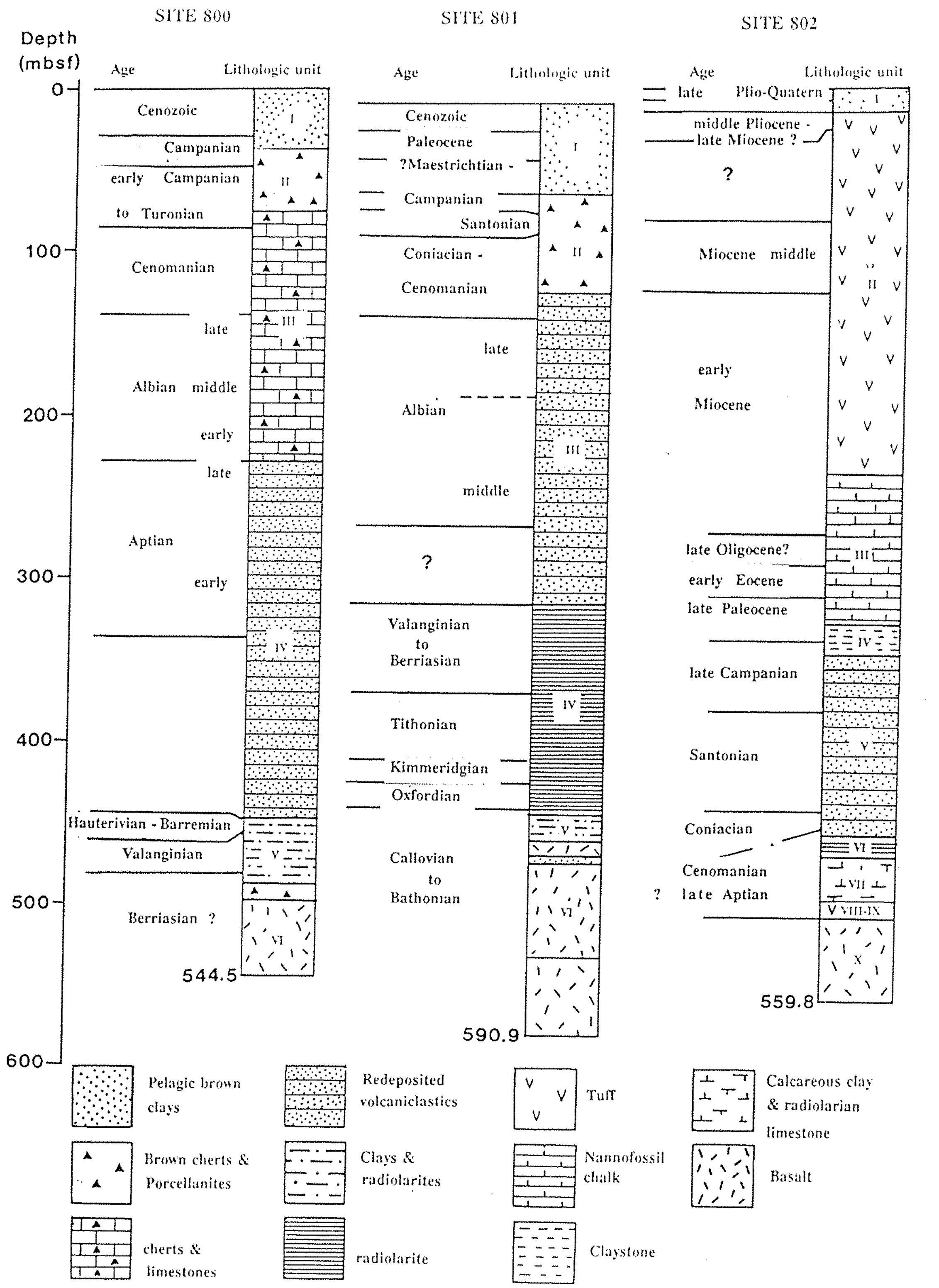

Fig 3. Summary of the lithostratigraphy for the ODP Leg 129 Sites 800, 801 and 802 (modified from Lancelot, E., Larson, R.L. et al., 1990).

of the final manuscripts (Papers 2, 3, & 4) were done by the second author (DAVS). For the 4th paper, the section called 'Physical context' and 'flow chart' are rewritten by the third author (RESC) in addition to the basic training and help in how to use the computer workstation for image enhancement (applicable for both 4th and 6th Papers). In the case of the 4th paper, the geological concept (basis) of the paper was justified by the second author (DAVS) who also made very useful corrections and logical additions to the manuscript of the 6th paper, as the supervisor of the research.

However, notwithstanding joint authorship of papers, the research work has been carried out solely by the research student (ARMS) who is also fully responsible for the principal findings reported.

I.B Scientific Objectives

The principal scientific objectives of this study can be divided to those concerned specifically with the sediment facies, those concerned with advancing our use and interpretation of wireline log data, and those concerned with the integration of sediment and wireline log data to allow comment on the geological evolution of the area under consideration. The specific objectives are amplified below:

I.B.1 Resedimented volcaniclastic facies and sequences:

i) to delineate sediment facies within the volcaniclastic units of the ODP Leg 129 sites in terms of texture, structure, and composition;

ii) to define facies models for each type of resedimented volcaniclastite, showing idealised vertical evolution of sedimentary features and to interpret these in terms of their specific process of deposition in a deep marine setting;

iii) to delineate the presence and vertical extent of the facies using wireline logs in sections with poor core recovery in order to infer the range of thickness of various facies;

iv) to introduce the concept of a typical vertical sequence of resedimented volcaniclastic and associated facies in mid-plate settings and its implication for regional volcano-tectonic activity.

I.B.2 Wireline log signatures of resedimented volcaniclastic facies:

I.B.2.1 general logs

i) to document the signatures of various wireline logs in the different facies present within the volcaniclastic units, having first compared these carefully with the recovered cores ;

ii) to show how various combinations of logs can be used to enhance the delineation of facies within the volcaniclastic sediments;

iii) to introduce the methodology (approach) of recognising vertical sequences on the basis of wireline log signatures and their application for defining the sequences in terms of bed-thickness and gross grain-size in mid-plate basins.

I.B.2.2 FMS images

iv) to demonstrate how the FMS images can be used to:

delineate detailed sedimentary features of intervals with poor core recovery; delineate the original sedimentary features where these have been abraded or brecciated during drilling; recognise sedimentary facies in non-recovered coring intervals; and assign the correct location of short-length recovered portions within the known cored intervals.

I.B.2.3 enhanced FMS images

v) to introduce the notion of context in the dimension of FMS image data sequences;

vi) to show how across-borehole image data interpretations can be extrapolated to infer directional sedimentological interpretations;

vii) to introduce how sequentially enhanced FMS images can be used to correlate the various patterns of image-mottles caused from turbiditic bioturbation with possible deep marine ichnogenera; and to propose a slightly modified classification for turbiditic bioturbation.

I.B.3 Evolution of Pigafetta and East Mariana basins:

i) to use the characteristics of facies and facies sequences derived from sediment and wireline log studies (I.B.1 and I.B.2 above), and their variation within and between sites, in order to infer the evolution of depositional settings in Pigafetta and East Mariana basins;

ii) to integrate data generated in this study with those of other shore-based, and comparative regional studies in order to better understand the volcano-tectonic evolution of the basins, and the interplay of tectonic, sea-level and sediment supply controls on sedimentation.

I.C Data Base and Methodology

I.C.1 Shipboard participation

Two months were spent at sea on board Joides Resolution drillship as one of five shipboard sedimentologists. Much of the work on core description and facies determination was carried out during this period. Preliminary lithostratigraphic logs were prepared in collaboration with shipboard micropaleontologists. Ideas on basin evolution were discussed generally amongst all scientists present.

The sedimentologists then divided up the post-cruise work, with me taking special responsibility for the volcaniclastic sediments. I prepared a sampling programme accordingly returning with 111 samples. Sediment smear slides, thin sections, x-radiographs, and core photos were also taken at sea, and many of these are now on loan to me in Southampton.

I.C.2 Wireline log data/analysis

A full suite of wireline logs were run at sea as far as hole conditions would allow. A technical summary of the main wireline logging methods used in this study, is presented as the appendix (section) of the thesis. The data set includes:

I.C.2.1 geophysical logs:

1) calliper (CALI & CAL1 in inches;)
2) total gamma ray (SGR in API units;)
3) microresistivity
4) dipmeter (MSD, CSB, and LOCDIP processed, in degrees and azimuths)
5) FMS* images (static-, dynamic- and HILITE-normalisation images; scale 1:5)
6) FMS* images (first-, second-, and third-order enhanced images; scale 1:5)

I.C.2.2 geochemical logs:

elemental logs (original & processed):

(1) calcium yield (CCA in decimal fraction)

(2) silicon yield (CSI in decimal fraction)

(3) lithology indicator ratio (LIR = CSI/(CSI+CCA))

Although much work can be carried out on copies of these wireline logs as processed by the ODP Borehole Logging Group at Lamont Doherty Geological Observatory (LDGO), further processing of the FMS, dip-microresistivity logs for detailed sedimentological studies was found to be necessary. I therefore spent a period of three weeks (March-April, 1991) at LDGO learning the processing technique and then processing the logs for certain intervals of volcaniclastic sediments of particular interest to my study. During the final stages of research, in order to carry out a specific research on finding the required order and degree of FMS image enhancement with a view to achieving very fine scale resolution in terms of sedimentary features (e.g., subtle lithology discrimination; ichnofossil recognition from image mottles) and fine scale sedimentary interpretations, 6 weeks (July-August, 1992; and February, 1993) were spent at Schlumberger, London.

The analysis and interpretation of these logs, at a scale of detail not previously attempted, has formed the basis of much of my post-cruise work to date.

I.C.3 Sediment data/laboratory analysis

Much of the conventional sedimentology has been completed on board the ship and in the few months post-cruise, using visual core descriptions, core photographs, and x-radiographs, as well as smear slides and limited thin section data.

I.D References

Lancelot, Y., Larson, R.L., *et al.*, 1990. Proc. ODP, Init. Reports., 129: College Station, Texas (Ocean Drilling Program).

DISCUSSION

The main thrust of this thesis has been to attempt some kind of computer based approach in sedimentology, taking examples from resedimented volcaniclastites, recovered during ODP Leg 129 from the West Central Pacific. In particular, it is concerned with the conversion of sedimentological knowledge from rocks to wireline logs (in the form of wiggles, tadpole-plots, and images) and vice-versa, following various methods of calibration, correlation, interpolation, and extrapolation. For this kind of approach, the science of pattern recognition plays a vital role. Because the physical and chemical properties of rocks are never strictly uniform, so the resultant signals and processed wireline log signatures will also vary. Although, for our purposes, data acquisition, data processing, and data enhancement by computer, have a discrete dimension, there is also an important role for an expert knowledge-based system to help eliminate defaults in data-sequence (e.g., artifacts, noise, etc., in the case of FMS images; Bourke, 1989) as well as to enhance the data-grade (e.g., enhanced FMS images), in order to achieve subjectively qualified data and consequently an improved interpretation-application (context).

D.I Sedimentological Applications of Wireline Logs: A Brief Literature Review

Selley (1992) distinguished three phases within the context of 'Wireline Logging', since its introduction in 1927 that show a progressive enhancement of the method in its technical complexity and range of application. These include: (a) hydrocarbon detection (first age); (b) porosity/lithology determination/delineation (second age); and (c) mineralogy/geochemistry/diagenesis study (third age). It is suggested here that the present progression towards finer and finer scale resolution to 1 cm of sedimentological and structural features from FMS/FMI images and their refined interpretations (e.g., Bourke, 1992; Salimullah & Stow, 1992) can be considered the fourth age in the scientific application of wireline logging.

On the other hand, the scientific applications of downhole measurements in the present ocean basins, under the auspices of the Ocean Drilling Program (ODP) and their future developments, have been well summarised by Worthington *et al.* (1989).

In the following discussion, an attempt is taken to highlight the major sedimentological applications of various wireline logs in a simple but discrete style without dealing specifically with the hierarchy involved in data-processing methods/parameters nor with the approach taken for their interpretation.

D.I.1 Petro-facies: porosity logs

Various combinations of the porosity logs (e.g., density, sonic, neutron logs) have been widely used (e.g., Asquith & Gibson, 1982; Serra, 1986a & 1986b; Schlumberger, 1991a) to delineate major rock-types (e.g., sandstone/shale/carbonates/evaporites; etc) using techniques such as overlay, cross-plot, formulated inversion, etc.

D.I.2 Lithology/texture: lithology logs

The interpretation of lithology logs (e.g., spontaneous potential, gamma ray logs) in terms of grain-size (large extent) and of composition (e.g., sandstone vs. limestone; small extent) has been widespread (e.g., Asquith & Gibson, 1982; Cant, 1984; Serra, 1986a,1986b, 1989). Moreover, the vertical pattern (shape/motif) analyses of these logs, in terms of vertical grain-size evolution (e.g., fining- and coarsening-upward), has been widely used to infer depositional morphological element(s) within a specific environmental or tectonic setting (e.g., Cant, 1984).

Although, this kind of straight-forward application has been criticised by Rider (1990), from consideration of the various drawbacks inherent in the nature of the data-base (e.g., artifact) and from spurious data-interpretations (e.g., lack of ground-truths, over-simplification, etc). For example, Imam and Trewin (1991) have shown for the North Sea Claymore Sandstones that high values (50-170 API) of gamma ray logs are not necessarily related to small grain-size (e.g., clays) but can also be caused by a highly radioactive composition (potash feldspar, zircon, & monazite).

Apart from this kind of conventional application, the enhanced (signal) processing of gamma ray logs along with other data sets (e.g., FMS images; core barrel sheets), have been used to delineate Milankovitch cyclicity within the Jurassic and Cretaceous radiolarian sediments (Molinie, Ogg, et al., 1990; Molinie & Ogg, 1992).

D.I.3 Sedimentary feature/sequence: dipmeter-microresistivity logs

Textural interpretations of heterogeneity or homogeneity in grain-size distribution in the case of massive beds or units (e.g., conglomerates/breccias), and of monotonous planar bedding/lamination, and the recognition of overall grain size trends, in the case of turbidite beds and sequences, have been well documented by dipmeter-microresistivity signatures (e.g., Serra, 1986a, 1989a; Salimullah & Stow, 1992b; Delhomme *et al.*, 1988). The recognition and interpretation of sedimentary structures, including bedding contacts , slump folds, cross-bedding/lamination, graded bedding, etc. have also been presented by various authors (e.g., Serra, 1986a, 1986b, 1989a; Salimullah & Stow, 1992b; Hocker *et al.*, 1990).

Electro-facies sequence analysis, by vertical trend analysis of dip readings (magnitude) combined with the lithology log motives (mentioned above), has been used to delineate vertical sequences of depositional facies in terms of bed-thickness and grain-size trends (e.g., Serra, 1989a; Selley, 1979; Schlumberger, 1986a, 1986b; Shanmugam & Moiola, 1988). In addition, dip-azimuth interpretations have been used to infer the direction of bed/sequence pinch-out (geometry of certain reservoir intervals) from data extrapolation, and of palaeocurrent direction from cross-beds (e.g., Rider, 1992).

D.I.4 Sediment chemistry/diagenesis: geophysical/geochemical combination logs

Delineation as well as differentiation of rock-types based on major rock-chemistry, by cross-plots of the various data sets derived from the porosity logs mentioned above, are widely known (e.g., Serra, 1986a, 1986b). But the combination of lithology logs (e.g., gamma ray logs) and porosity logs (e.g., sonic, density logs) has been uniquely documented in relation to delineation of diagenetic facies (e.g., uncemented sands, carbonate cemented horizons in conglomerates, phosphatic cements) in reservoir rocks (Selley, 1992; Humphreys & Lott, 1991), as well as compactional features in various rock-types (Serra, 1986b). Recently developed elemental- (10 elements) and oxide-logs (processed geochemical combination logs) have become increasingly popular for: (a) identifying rock-types in poorly recovered intervals (Salimullah & Stow, 1992a), (b) mineralogical discrimination and sandstone classification (e.g., Herron & Herron, 1990), and (c) determination of mineralogy in a volcanic sequence (e.g., Harvey and Lovell, 1992). Apart from this kind of application, a complex combination of geophysical- and geochemical-logs, has been adopted to document sediment intervals containing various proportions of total organic carbon (TOC) within a known source rock-unit (e.g., Fertl and Chillinger, 1988; Stocks & Lawrence, 1991; Myers & Jenkyns, 1992). FMS images have been uniquely use to recognise the presence of various diagenetic features including stylolites, cherts and anhydritic nodules, and hard-grounds in carbonates (Serra, 1986b).

D.I.5 Sediment facies: FMS images

Sediment facies, defined in terms of texture and structure (inorganic and biogenic), have been delineated by FMS images to progressively finer and finer scales since the introduction of the FMS logs in 1986 (Ekstrom et al., 1986). Sedimentary features at a scale of 1 cm from a variety of different sediment facies, have been uniquely documented by dynamic and hilite normalisation images (Boyeldieu & Jeffreys, 1988; Trouiller, J-C., et al., 1989; Serra, 1989a, 1989b; Harker et al., 1990; Luthi, 1990; Salimullah & Stow, 1992b). Suitably enhanced 2D/3D FMS/FMI (formation micro imager) images of a specific depth (data) interval, with in-depth sedimentological (subjective) knowledge in relation to interpretation-application context, can be used to document a 3-dimensional picture of a particular sedimentary structure (e.g., Bull's eye; Schlumberger, 1991b & 1992), and directional interpretations of a sedimentary bed (e.g., possible pinch out/palaeo-flow direction; Salimullah, Stow, & Cull; in press).

D.II Synthesis of Papers/Manuscripts Presented in this Thesis

The main theme of the six manuscripts (papers), which constitute the dominant portion of this thesis, has been the application and interpretation of wireline logs, in particular FMS logs, within the field of deep marine sedimentology, taking examples from the ODP Leg 129. Although this study has concentrated on volcaniclastic rock intervals/sections, the methodology would be generally applicable to any other rock-type (e.g., siliciclastic/carbonate).

In the following sections, an attempt is taken to summarise:
(a) how the basic sedimentology from recovered cores as well as from published texts has been transferred to the wireline logs and vice-versa; and (b) how far it is possible to push interpretation of the logs (in terms of scale and degree) within the available facility of data processing.

D.II.1 Knowledge from rocks (see paper 1)

The recovered cores of the volcaniclastic units in all the sites displayed well preserved sedimentary features (texture, structure and composition). On the basis of vertical evolution of these sedimentary features in certain well-recovered coring intervals, the entire volcaniclastic sections are divided into seven genetically related sedimentary facies: debrites, slumps, fluidized-flow deposits, grain-flow deposits, volcaniclastic turbidites, calcareous volcaniclastic turbidites, and pelagic sediments and bioclastic turbidites.

D.II.2 Conversion of rock-knowledge to wireline logs and vice-versa (see papers 1 & 2)

The sedimentary features observed in rocks and their vertical evolution are directly calibrated with the various wireline logs in the case of well-recovered coring intervals. On the other hand, where cores are scarce or disturbed and/or wireline log signatures show dissimilarity with those that are already calibrated, they are compared with the published data-base where possible. Next, these log signatures are correlated with the respective interpretation-context. However, if some log signatures do not fall into either of the two categories mentioned above, the physical interpretation of these signatures are correlated with known sedimentary features largely by means of pattern recognition.

D.II.3 Wireline log signatures of sedimentary facies (see paper 2)

Following the above mentioned methodologies in terms of translation/conversion of the rock-knowledge to the wireline logs and vice-versa, the discrete signature of each kind of wireline log in relation to each sediment facies is established. The fine-scale sedimentary features (e.g., lamination) are firstly documented by the FMS images, because these have the highest feature-resolution capability among the wireline logs which are used in this study. Then, each sedimentary facies, in the form of beds or packages of beds, are correlated with the other available wireline logs (dipmeter-microresistivity, gamma-ray, geochemical logs).

D.II.4 Application of wireline log signatures (see papers 3 & 5)

The interpolation/extrapolation of the wireline log signatures, representing various sedimentary features as well as depositional sedimentary facies, are used to translate/convert the entire sections/intervals (metre by metre) within the volcaniclastic units, for which wireline logs were successfully recovered (Lancelot & Larson *et al.*, 1990). Thus, a new visual description for each coring interval is produced, that has been called 'FID' (Salimullah & Stow, this volume). These FIDs provide a more complete sedimentary picture than previously and eliminate any sedimentary data-gaps and drawbacks caused from poor core-recovery, core-disturbances (e.g., drilling breccia), non-core-recovery, and core-depth-matching. From this kind of additional data base, the vertical continuity and distribution of each sedimentary facies are delineated in order to construct vertical sequences of the facies at each of the sites and so to infer tectono-sedimentary evolution of the study basins (Pigafetta and East Mariana Basins).

D.II.5 Context in FMS image sequences (see paper 4)

The FMS image interpretations have formed the finest scale (about 1 cm) of resolvable sedimentary feature (e.g., bioturbation, lamination, etc) among any of the other wireline log interpretation used. They have therefore formed the basis of all the interpretation and application made in this study. To consider this fact, a kind of model in relation to the sequences in the FMS image data, is prepared, taking samples from a volcaniclastic turbidite bed. The whole data set is divided into three contexts: physical, global, and local. The physical context involves largely the physical aspects of the images and is related largely to image restoration processes. The global context involves traditional/routine-type data which are used globally for the first order subjective interpretation (e.g., turbidite recognition) and is related to image normalisation processes. The local context involves enhanced images which are used for the second- and third-order subjective interpretations (e.g., details within a turbidite bed), and is related to image enhancement processes.

D.II.6 Volcaniclastic turbidite sequences from wireline log interpretations (see paper 5)

As mentioned above (D.II.4), with the help of wireline log signatures including FMS images (FIDs), the complete volcaniclastic successions of each site is considered, in terms of vertical distribution of the resedimented facies. These successions are considered as the first-order or macro-scale (>100m) sequences. Their genesis is compared with the existing archipelagic apron model of volcanic sequences (Kelts & Arthur, 1981) and used to a propose a new model, in terms of distance between source-seamounts and depositional sites, by Salimullah and Stow (paper 5). From these resedimented facies sequences, it is possible to extract the second-order or meso-scale (10-100m) sequences and the third-order or micro-scale (< 10 m) sequences, in terms of bed-thickness evolution and signature determined from the FIDs. These meso- and microsequences are characterised by dipmeter and gamma ray log patterns in terms of bed-thickness and grain-size respectively. They are further supported by structural (sedimentary) details, compositional data, and turbidite frequency calculations. To combine the interpretation of all these data sets, the tectono-sedimentary evolution of the source areas as well as the basins is characterised and their likely controls inferred.

D.II.7 FMS images in ichnogenera recognition: an introduction (see paper 6)

Unlike any other wireline logs used in this study, the analysis of FMS images, like any other images, is based largely on their textural and geometrical aspects. Since bioturbation marks preserved in sedimentary rocks reveal both textural and geometrical features, it should be possible to recognise and even to classify burrows using FMS image patterns (shape/size). Previous published work in this area is limited to documenting the trace fossil marks by FMS images as taphonomic signatures, but not as ichnogeneric signatures. In this study, an attempt is made to document six types of image pattern of the highly bioturbated volcaniclastic turbidite/hemiturbidite beds by sequential image enhancement. Then, these FMS image patterns are correlated with the possible ichno-toponomic features observed in recovered rock pieces and/or with known deep marine ichnogenera (e.g., Wetzel, 1991). However, due to the lack of qualitative image data, the present interpretation must be limited to the recognition of some ichnogenera from the FMS images and not to amplification of their ecological implications.

Furthermore, a slightly different scheme of turbiditic bioturbation is proposed from FMS image studies, with due consideration to existing concepts and classifications of bioturbation and more specifically that of turbiditic bioturbation made in actual sediments and rocks. Finally, volcaniclastic hemiturbidites are delineated within the volcaniclastic turbidite facies with the help of enhanced FMS images.

D.III Scope of Further Research

In any research, there always remains scope for continuity in terms of finer to finer scale resolution, and of diversity in application. Finding the positive progression in the said dimension, is largely an interaction of ability, time, and technical facility. To consider this fact, an attempt is made below to outline the scope of possible research, which might follow on from the present thesis work, in three specific areas.

D.III.1 Significance of fine scale FMS dip vs. FMS image signatures

Among the seven resedimented facies delineated in the volcaniclastic units, Leg 129, slumps, debrites, fluidized-flow deposits, grain-flow deposits, and volcaniclastic turbidites, are discriminated from each other on the basis of texture and/or structure (Salimullah, 1992). The vertical sequences of facies recognised in this study typically show a coincident evolution in the nature of internal features of the constituent beds. These internal features have characteristic geometry and texture which are largely imitated in enhanced FMS images. Moreover, many of the structural features (e.g., graded bedding, lamination) are mirrored by textural (grain-size) variation.

FMS correl curves (resistivity traces) corresponding to the FMS images representing these textural/structural features, reveal uniquely the skeletons of the images which show relative similarities with the structures, and thus confirm the FMS image interpretations. On the other hand, FMS dips (azimuths), corresponding to FMS images and FMS correl curves representing any sedimentary structures, show unique relations in terms of dip-magnitude (increase/decrease/uniform) as well as dip-direction (change in direction) with specific elements (e.g., recumbent folds in slumps, angle of forsets in cross beds/lamination, no dips or random dips in massive beds, etc) of the structures. This leads to a still higher degree of confidence in FMS image interpretations. This kind of FMS dip- versus FMS image-signature established either by calibration or by correlation, can be used to delineate detailed internal features of any sedimentary facies down to 1 cm resolution including the deep marine ones studied in this thesis irrespective of the degree of core-recovery. Thus, fine scale sedimentary-process-dynamic (e.g., hydrodynamic) interpretation can be achieved.

D.III.2 Application of FMS images in core orientation studies

Core-orientation, in the general case, means the true orientation of the recovered cores with respect to that of the borehole walls. But in other cases, for example, where there is poor-core-recovery, core-disturbance or fragmented-core-recovery, core-orientation also implies: (a) depth-matching of recovered cores; (b) checking the correct vertical orientation of core pieces, that may become misplaced during handling; and (c) recognising the intrusion of core-pieces from the overlying coring interval. Since FMS images provide a continuous picture of borehole walls with absolute orientation, by calibration with specific sedimentary features (e.g., bifurcated burrows, bedding contacts, etc) the image interpretations can be used in this kind of highly sophisticated core-orientation. This application of FMS images has been partly documented for ODP Leg 129 cores in this thesis, but much further work is still required.

D.III.3 Finding sedimentary causes of core-loss from FMS image studies

Average core-loss of the study sites used in this thesis ranges from 71-84%, with a maximum of 90-100%.

In this kind of situation, how FMS images can be applied to provide and enhance sedimentary data-interpretations, has been documented (Salimullah & Stow, 1992b; paper 3 this thesis). Further research in this line suggests that there is a unique relation as well as coherence between a degree (range in percentage) of core-loss and a dominant-type of sedimentary facies (in terms of texture and structure) within a coring interval. To consider this fact, the whole dimension of core-loss, in volcaniclastic intervals of ODP Leg 129, is divided into four aspects: (a) core-loss in homogeneous massive intervals; (b) core-loss in lamination-dominated intervals; (c) core-loss in bioturbation-dominated intervals; and (d) core-loss in slump-dominated intervals. Although, the water depths of the sites (5.6-5.8 km) may be a reasonable factor side by side with the mechanical aspect of drilling in terms of core-loss, they are uniformly applicable to all coring intervals irrespective to lithology and/or geometry of sedimentary rock-beds. Hence, it may be possible to provide philosophical interpretations of core-loss in terms of sediment-texture (e.g., size, sorting, grading, homogeneity/heterogeneity), bed-geometry (e.g., orientation of beds, bed-attitude), rock-mechanics (e.g., hardness, consolidation, fragmentation, groundness), and coring-mechanics (e.g., bit action, core-entrance in core-barrel, role of core-catcher; etc).

D.IV Conclusions

The major findings of this thesis can be summarised in the following points:

1. The characteristic signatures of various wireline logs, including FMS images, dipmeter-microresistivity and gamma ray logs, of resedimented volcaniclastic facies and their vertical sequences in mid-ocean basins, have been documented for the first time.

2. A refined methodology for the application of these log signatures, specifically of FMS images, to delineate resedimented volcaniclastic facies under conditions of core-loss, core-damage, and non-cored intervals, has been developed.

3. FMS image descriptions (FIDs) have been introduced to replace visual core descriptions (VCDs) in order to obtain a relatively complete sedimentary picture of a coring interval in the situations mentioned in (2). These FIDs can be considered as a routine logging task in the ODP as well as in petroleum industries.

4. Careful use of FMS/dipmeter and gamma ray logs has been made to delineate and to characterise turbidite sequences of various scales (macro-, meso-, and microsequences), in mid-ocean volcaniclastic successions. In particular, new types of microsequences, oscillation and saw-tooth sequences, have been introduced for the first time.

5. A new refined model of vertical sequences for an archipelagic apron and its extension up to a mid-ocean basin, controlled by the distance between source seamounts and depositional sites, has been introduced for the first time.

6. The existing standard grading scheme for FMS image interpretation-application (context) by Serra (1989b), has been modified and enhanced.

7. The context of FMS image (data) sequences, through a computer automated approach (in the domain of computer vision), based upon only one volcaniclastic turbidite bed, has been introduced, and can be used as a kind of data model by Wireline Geologists/Sedimentologists.

8. A sequence of enhancement of FMS images, in order to recognise patterns of bioturbational image mottles and their possible correlation with deep-marine ichnogenera and ichnofacies, has been proposed as well as documented for the first time. Volcaniclastic hemiturbidites have thus be identified.

9. Above all, the concept of sedimentology from wireline logs, that is <u>Wireline Sedimentology</u>, has been further advanced, taking due account of previously published sedimentological applications of wireline logs. Although, this thesis contains examples from deep marine volcaniclastic rocks, the basic principles of conversion of conventional sedimentology to wireline sedimentology and vice-versa, are equally applicable to any other sediment/rock-type deposited in any other environment.

10. Further research in line with appropriate technical and financial capabilities (e.g., computer work stations, softwares, data-bases, etc), may further enhance the application of wireline logs, specifically of FMS images to study aspects of core-orientation and core-loss more precisely. On the other hand, the qualitative FMS image interpretations presented in this thesis, can be quantified using relevant sofware interactively. This can enhance the degree of confidence of the subjective applications including the ichnofacies recognition.

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APPENDIX

WIRELINE LOGGING METHODS: A Technical Summary

A.1 Introduction

Since the introduction of Wireline logging techniques by Schlumberger Brothers in 1927, with a view to delineating petrophysical properties of petroleum reservoirs, this logging method has become more and more sophisticated and evolved partly as a result of a continuously evolving engineering science. The main aspects of wireline logging are two fold: a) geophysical logging: that deals with petrophysics; and b) geochemical logging: that deals with petrochemistry. In the following sections, an attempt is taken to highlight the methods (that are used in this study) of these two aspects of logging in terms of their: a) principles (physics of the technique); b) tool concepts (tool- mechanics/configurations); and c) data acquisition and processing (primary). On the other hand, since this study is based on Ocean Drilling Program (ODP) material, hence the examples (e.g., tool configuration) are largely taken from that context where available.

A.2 Geophysical Logging

Geophysical logging involves measuring various petrophysical properties (e.g., density, porosity, acoustic impedance, fluid-content, etc.), using various physical techniques based upon fundamental energies/forces (e.g., electricity, seismicity, magnetism, radioactivity, etc.). In this study, electrical logging methods are used extensively, whereas radioactive methods (i.e., gamma-ray logs) and geochemical logging are used minimally. Moreover, among the various electrical logging tools, only two kinds are used in this study: the dipmeter-microresistivity tool and the Formation MicroScanner (FMS*) tool. Since this study is based largely upon the FMS data/images and the FMS tool and its basic concept is a hybrid of the dipmeter tool, the following discusssion will focus on the FMS technique. However, there are significant differences between this two techniques in terms of data acquisition, data processing and interpretation-application (context), so those readers specifically interested in the dipmeter technique are referred to the relevant literatures (e.g., Schlumberger, 1986a; Rider, 1990, 1992; Delhomme et al., 1988; Hocker et al., 1990).

A.2.1 FMS tool concept

The physical rock property on which the FMS tool works is electrical resistivity variation near the borehole walls. The tool (Fig. 1) is a pad-based, passively-focussed resistivity measuring device, the physics of which is essentially based on quasi-electrostatics (Ekstrom et al., 1986). A conducting pad is articulated to the borehole surface. The pad is an equipotential surface, held at a constant potential

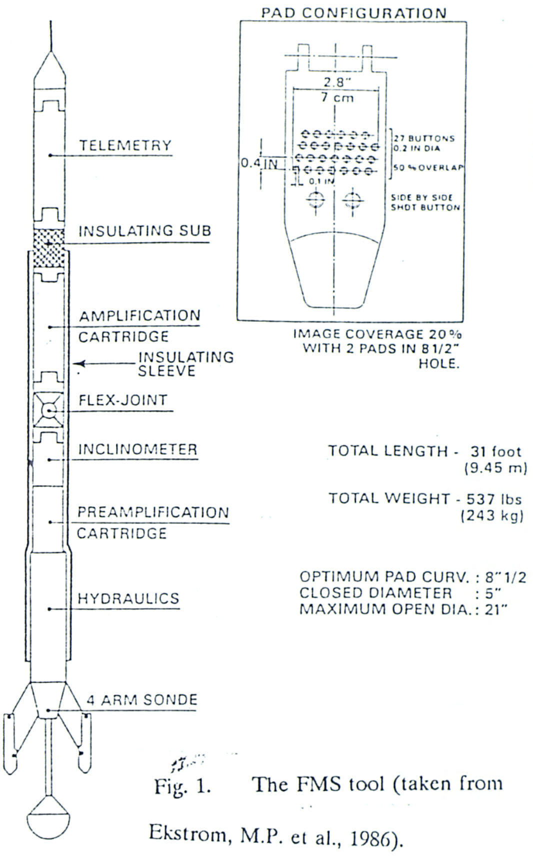

Fig. 1. The FMS tool (taken from Ekstrom, M.P. et al., 1986).

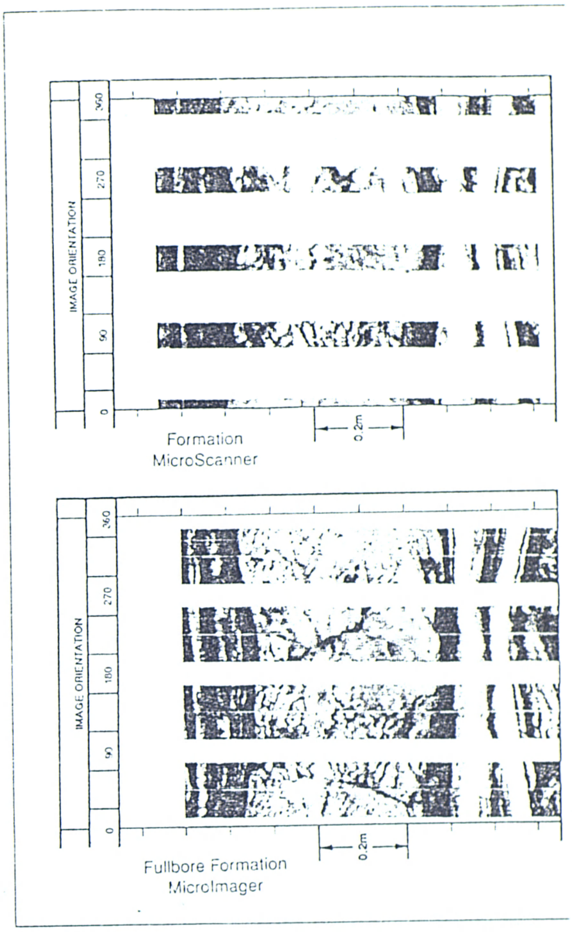

Fig. 3. Comparison of borehole coverage of FMI and Formation FMS images (from Schlumberger, 1992).

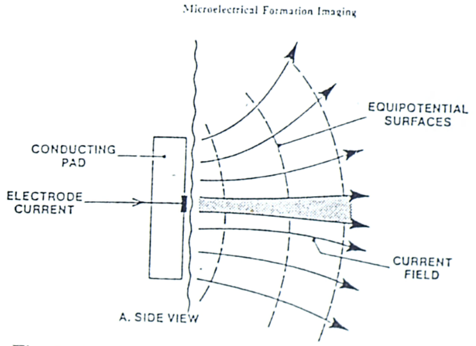

Fig. 2a. Pad/electrode configuration for microresistivity measurements (from Ekstrom, M.P. et al., 1986).

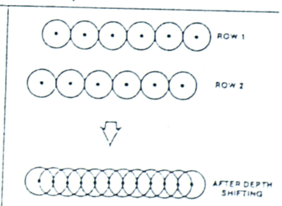

Fig. 2c. Staggered electrode array with overlapped sampling (from Ekstrom, M.P. et al., 1986).

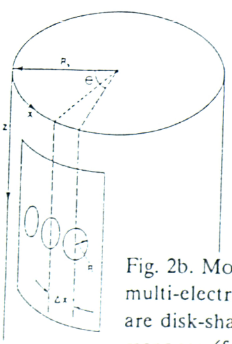

Fig. 2b. Modelling representation of multi-electrode pad. The electrodes are disk-shaped for isotropic response (from Ekstrom, M.P. et al., 1986).

relative to a return electrode (located in an upper section of the borehole), and this pad injects current into the formation (Fig. 2). The current density across the pad is determined primarily by local resistivity variations in front of the pad. Thus, by sampling this current distribution, we obtain directly a characterisation of the formation microresistivity over the borehole surface spanned by the sampling aperture (for further details, see Ekstrom et al., 1986).

The original FMS tool has been modified for the sake of the narrow diameter ODP boreholes (see, paper 3, this volume). It has also evolved in terms of the number of pads, from two (initially) to four (Fig. 1a) and presently to eight (called Fullbore MicroImager or FMI*, see FMI* dossier, Schlumberger, 1991, 1992). This linear increment of pad-number has resulted in an incremental increase in coverage of the borehole walls (Fig. 3).

A.2.2 FMS data acquisition guidelines

A.2.2.1 mud programme

Since the tool sends an electrical current into the formation, it theoretically works only in water-based mud (Serra, 1989b). The mud resistivity should not exceed 50 ohm-m; however the mud must not be too conductive. For good image quality, the contrast in resistivity between the mud and the formation should be below 10.000 ohm-m. When the mud is too conductive relative to the formation, the current tends to flow into the borehole, reducing the sharpness of the images. FMS data can be recorded in oil-based muds if the water content is at least 30-40%.

A.2.2.2 borehole coverage

One pass of the two-pad tool covers 20% of the borehole wall in an 8.5" hole. Making repeat-runs with the tool rotating between each run will increase borehole coverage and lateral continuity. The four-pad tool doubles (40%) and the eight-pad tool quadruples (80%) the said coverage of the two-pad tool in one run.

A.2.2.3 borehole deviation

With borehole deviation less than 10 degrees, centralizing the tool minimises poor pad contact caused by oblique positioning of the tool compared to the borehole axis. Imperfect pad contact caused by drilling-related ovalisation of the borehole may result in a blurred image. The tool can be used in horizontal wells with the use of the Tough Logging Condition (TLC*) system.

A.2.3 Image processing

The aim of processing is to convert the button current intensity measurement into variable-intensity grey-scale or colour images. The major steps are summarised below:

A.2.3.1 depth shifting

Since the rows of buttons are at different vertical positions on the tool, the individual button responses must be depth shifted by an amount equal to the distance between the upper pad row and the row in which the button is found (Schlumberger, 1992). The shifts for the lower rows on the pads are o.3"; the shifts for the upper and lower rows on the flaps are 5.7" and 6", respectively.

A.2.3.2 image generation

The data acquired by each pad and each flap are processed as a matrix, with an azimuthal element for each button and a vertical element for each depth for which measurements are obtained. Normally, both the horizontal and the vertical elements are sampled at 0.1" intervals. Each matrix element is represented on the image by a colour spot whose dimension depends on the azimuthal and vertical scales of chosen image (Schlumberger, 1992).

A.2.3.3 equalisation

Raw tool measurements can be affected by drift in electronic circuits, uneven sensor application or other factors. Equalisation is a technique that compensates for differences in gain and offset of the sensor responses by replacing each sensor gain and offset by the mean gain and offset of all the sensors computed in a user-defined sliding window. Typically, the length of the window is set to 15 ft. Other options use statistical methods to detect and correct for dead buttons and EMEX current variations (Schlumberger, 1992).

A.2.3.4 speed correction

The depth shifting described earlier does not account for irregularities in the tool motion; it is necessary to compute the effective depth of measurement of each sensor. Two techniques are available to perform this correction: double integration of the tool acceleration, and correlating the response from the adjacent rows of the sensors and recomputing the actual depth of the measurements (Schlumberger, 1992).

A.2.3.5 normalisation

The normalisation is used to define the limits of the image colour classes. A histogram of the data is computed and the total range of is partitioned into 17 (for grey-scale) or 42 (colour-scale) classes, each with the same data count. This results in an equal area for each grey/colour range on the final picture. By default, the 17 or 42 grey/colours range from white (resistive) through orange to black (conductive). Other colour scales, using shades of grey and brown, are available (Schlumberger, 1992). There are two types of normalisation:

<u>Static normalisation</u> involves defining the grey/colour classes of the entire set of data. It is best suited for observing large-scale resistivity variations. <u>Dynamic normalisation</u> recomputes the grey/colour scale

to be applied over a shorter, user-defined, sliding depth window and is used to detect small-scale resistivity contrasts (for details, see Schlumberger, 1989; paper 4, this volume).

A.2.4 FMS image interpretation-application

A.2.4.1 image interpretation approach

The degree and classes of grey/colour tones of the FMS images represent the resistivity/conductivity of the borehole walls/geological formation, providing that the images are beyond the defection related to various image artifacts (Bourke, 1989, 1992). The straightforward translation of the FMS images is that white/lighter grey means resistive- and the black/darker grey means conductive-events of the geological formations. The in-between grey/colour tones relate to an intermediate scale of resistivity/conductivity events of the formation. The primary control over the grey/colour tones may be related to various petrophysical properties of the formation, including grainsize, porosity, fluid-content, grain density and so on. Hence, image calibration with the recovered rocks is essential to a certain extent (for details see paper 3 & 6, this volume).

A.2.4.2 application

The FMS images can be applied in several areas of study including sedimentology, petroleum geology, structural geology, and petroleum engineering (see Schlumberger, 1986b; Serra, 1986a & b, 1989a & b; this volume). The main theme lies in their capacity of fine scale (up to 1 cm) resolution of resistivity events related to various subjective features including sedimentary structures (e.g., lamination). On the other hand, they provide a continuous picture of the borehole walls, thus facilitate uninterrupted subjective picture of the formations. They also enhance the subjective interpretation of the other kinds of borehole-log data (e.g., gamma ray, dipmeter, etc.) that have lower degrees of feature resolution.

A.3 Geochemical Logging

Geochemical logging involves nuclear measurements of borehole walls in the forms of natural gamma radiation, aluminium activation, capturing gamma ray spectroscopy, and gamma ray interactions, that are related to four separate tool-components (described below) comprising a Geochemical Logging Tool (GLT) (Lovell, Harvey, & Lofts, 1993). The principal aim of this logging is to obtain quantitative concentrations/measurements of 10 elements (Al, Si, Ca, Fe, S, Ti, K, Th, U, Gd, and possibly Mg) (Herron & Herron, 1990).

A.3.1 Geochemical Logging Tool (GLT)

The GLT (see Fig. 4) comprises four main components: the natural gamma-ray tool (NGT), the compensated netron tool (CNT), the alluminium activation clay tool (AACT), and the gamma-ray spectrometry tool (GST) (Pratson et al, 1992).

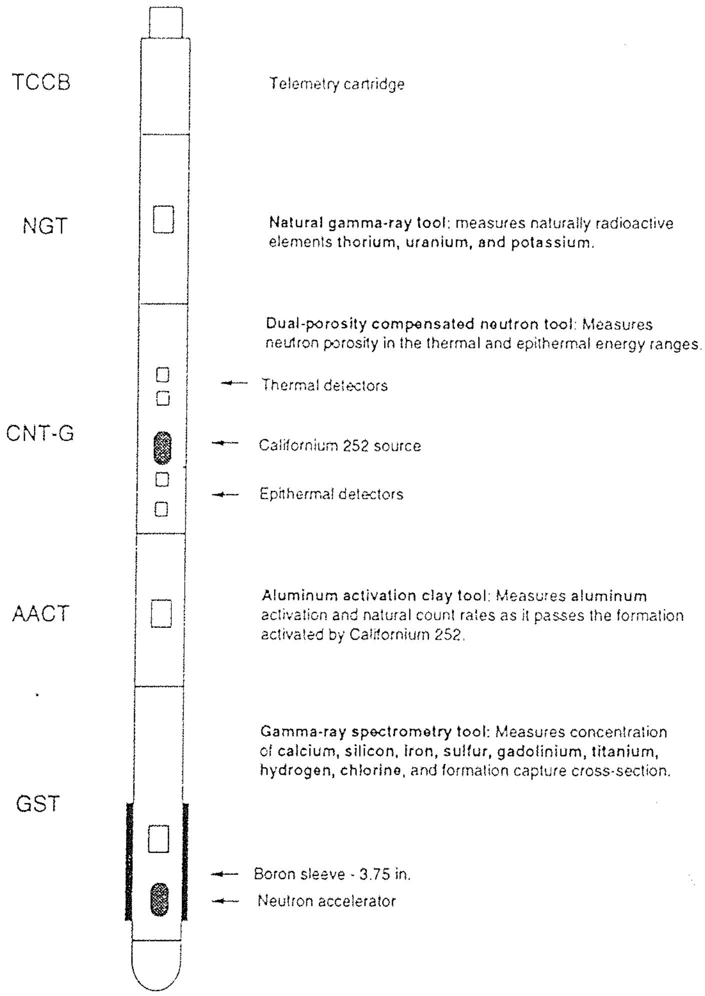

Fig. 4. Schematic drawing of the geochemical logging string used in the Ocean Drilling Program (taken from Pratson, E.L. et al, 1992).

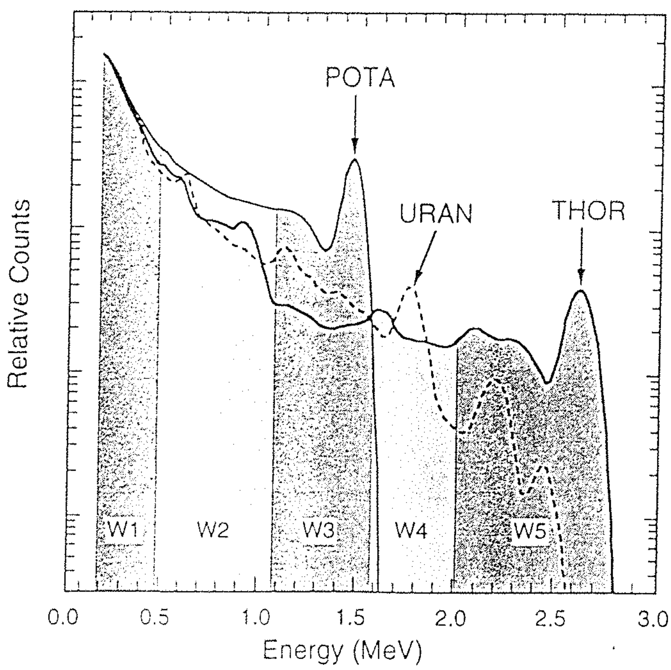

Fig. 5. Standard spectra from a natural gamma-ray-spectrometry tool (NGT) showing the relative counts of incident gamma rays versus their energy. The spectra are split up by the tool into five energy windows indicated by the shading. Windows 3, 4, and 5 cover the characteristic peaks of K, U, and T, respectively (taken from Lofts, J.C., 1993, unpublished thesis).

A.3.1.1 The NGT

The NGT measures naturally occurring gamma radiation as a function of the emitted gamma ray energy. This incident gamma- ray spectrum is divided into five discrete windows (energy ranges; see Fig. 5) among them three windows lie in the high energy part of the spectrum (windows 3-5) and denote the characteristic peaks of K, U, and Th (for details see Lovell, Harvey, & Lofts, 1993). The tool is located at the top of the GLT string so that the formation is maintained in as natural a condition as possible, as well as being uncontaminated by nuclear sources contained in other tools located below the NGT.

A.3.1.2 The AACT

The AACT tool measures Al concentrations of the formation. Gamma rays that result from delayed activation, by using a low energy californium source emitting neutrons at around 2.3 MeV, enables the determination of Al. The californium source is housed in a conventional neutron tool (CNT-G), positioned above the AACT in the string. The AACT tool is itself a modified natural gamma-ray tool (NGT) made to detect induced gamma-rays as well as the natural gamma ray signal. The net spectrum from Al is then calculated by deducting the NGT contribution determined from the NGT tool (mentioned above) (for details, see Lofts, 1993).

A.3.1.3 The GST

The Gamma-ray spectrometry Tool (GST) forms the third component of the GLT string and lies at the base of the string. The main principle of the GST involves higher energy neutrons (14 MeV) emitted from a mini-accelerator that are slowed down through scattering processes and their eventually captured at low thermal energy levels (<0.25eV) in order to produce prompt gamma-rays (Lovell, Harvey & Lofts, 1993). Since the energy of these emitted gamma rays is related to the element of origin, hence by using a spectral detector with 256 channels it is possible to separate out several elements. For an element to be determined it has to have a large thermal capture cross-section. The spectral signatures are then examined in terms of their degree of uniqueness/distinctiveness and of elemental concentration, with a view to finding out that an element can be resolved by this technique. Elements that can be determined by this tool include Ca, Fe, Si, K, S, Ti, Gd, H, and Cl.

A.3.1.4 The LDT

The Litho-density tool (LDT) uses the medium to low energy gamma ray interactions (Lovell, Harvey & Lofts, 1993). In a low energy condition, the photoelectric effect (Pe) provides an estimate of the mean atomic number of the formation. But in a medium energy condition, Compton Scattering enables to determination of the electron density (and thus bulk density for most geological materials).

It is evident that the techniques involved in the three tools mentioned above can be used to estimate all the major rock-forming elements, except for Na and Mg. However, from the LDT, it is possible to calculate a theoretical atomic number for these two elements. The difference between this estimate and that measured by the photoelectric effect is therefore attributable to (Na+Mg).

It is possible to determine insitu all commonly occurring major elements of the subsurface formations in the ODP boreholes, using this approach with an obvious exception to this being when a barium weighted mud is used. Then, due to the large photoelectric cross-section, the barium would contribute considerably to the missing Pe value. This condition is more common in other industrial cases rather than in the ODP. However, the drawback in the case of the ODP lies where the hole becomes large and filled with seawater, the hydrogen and chlorine contribution to the prompt gamma ray spectroscopy can be very large.

A.3.1.5 AMS

The auxiliary measurement sonde (AMS) located at the top of the GLT string measures resistivity and temperature of the borehole fluid, facilitating determination of the salinity and effective abundance of chlorine. It is therefore possible to estimate the borehole neutron capture cross-section (Lovell, Harvey & Lofts, 1993).

A.3.2 Geochemical Log-Data Processing Methods

The well log data from the tools are transmitted digitally up a wireline and are recorded and processed on the JOIDES Resolution. The results are made available as "field logs" for initial shipboard interpretation. Subsequent reprocessing is required to correct the data for the effects of fluids added to the well, logging speed, and pipe interference. Processing of the spectrometry data is necessary to transform the relative elemental yields into oxide weight fractions (Pratson et al., 1992). The processing is performed with a set of log interpretation programmes. The major steps are summarised below (for details, see Pratson et al., 1992; Lofts, 1993; Lovell, Harvey & Lofts, 1993):

1. **reconstruction of relative elemental yields from recorded spectral data:** this involves a weighted, least squares method to compare the measured spectra from the geochemical spectrometry tool with a series of standard spectra in order to determine the relative contribution (or yield) of each element.
2. **depth shifting:** In the course of geochemical processing data from different tool runs are combined. It is important to depth correlate all data to one reference run. A total gamma ray curve (from the NGT, which is run on each tool string) usually is chosen as a reference curve, based on cable tension and cable speed.
3. **calculation of total radioactivity and Th, U, & K concentrations:** this involves calculation of the total natural gamma radiation in the formation as well as the concentrations of Th, U, & K, using the counts in five spectral windows from the NGT.

4. calculation of Al concentration: this involves the calculation of an Al curve using four energy windows, while concurrently correcting for natural activity, borehole fluid neutron capture-cross-section, formation neutron-capture cross-section, formation slowing-down length, and borehole size.

5. normalization of elemental yields from the GST to calculate the elemental weight fractions: this routine combines the dry weight percentages of Al and K with the reconstructed yields to obtain dry weight percentages of the GST elements.

6. calculation of oxide percentages: this involves simple multiplication of the percentage of each element by its associated oxide factor (see table 1, Pratson et al., 1992).

A.3.3 Interpretation of Geochemical Log-Processed Data

The interpretation of the data can be qualitative or quantitative. Major rock-type delineation can be performed on the basis of gross elemental as well as oxide concentration of geological formations. This can be enhanced by calibrating/correlating the reprocessed log data with the quantitative laboratory data.

Sediment/rock cyclicity in terms of major elements (e.g., Si, Ca, Al, Fe) can be ascertained in spot cored or uncored wells using the geochemical logs. This can lead to subjective interpretations of, for example, Milankovitch cyclicity, depositional environment cyclicity, and so on.

A.4 Discussion

The progression of logging techniques lies mainly in their capacity of feature-resolution which in turn depends on the degrees of data sampling, data-interpretation, and interpretation-application (context). All these steps include sophistication in techniques/tools, computing/software, and interactive subjective knowledge.

The FMS tool, a hybrid product of the dipmeter tool, is able to collect data every 2.5 mm and the enhanced FMS images are able to resolve a resistivity event up to 1 cm scale. The data acquisition, data processing, image normalisation and image enhancement comprise the major steps in the FMS imaging dimension, each of which is a discrete field. Hence, this study has not attempted to further develop the methodologies involved, but rather to understand their limitations and apply the results.

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