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Deep drilling in an active geothermal area in the Azores

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A deep borehole on São Miguel encountered temperatures exceeding 200° C at a depth of 550 m. Subaerial volcanics persist to a depth of 786 m below sea level and indicate an average subsidence of 0.1 cm yr^{-1} for the island over the past 690,000 Myr.

Deep drilling is essential to the understanding of the process of the formation of oceanic islands. The petrology and geochemistry[1] of island rocks differs significantly from those of deep ocean crustal rocks and the structure underlying islands as defined by geophysical data differs from that beneath deep ocean floors. The contrast suggests that special deep processes operate beneath oceanic islands. Most volcanic islands are confined to near spreading plate margins during their active period and their formation may be associated with the ocean floor spreading process[2,3]. Periodically, voluminous volcanic activity indicates exceptionally high rates of subcrustal convective heat transfer and mantle hot spots or plumes have been postulated as the sources of this activity[1,4].

In 1972 geoscientists from Dalhousie University and Lamont–Doherty Geological Observatory initiated a deep drilling programme into the oceanic crust with an 800 m hole into the island of Bermuda in the western Atlantic[5–7]. It yielded some 1,000 volcanic units approximately equally divided between thin altered tholeiitic pillow lavas and lamprophyric intrusive sheets. Our second borehole in 1973 was located on the island of São Miguel, in the Azores, and an initial report is presented here of the 981 m penetration of a complex sequence of subaerial and submarine lavas, pyroclastics and volcanogenic sediments.

The Azores form a group of nine islands aligned in a NW–SE trending chain which transects the Mid-Atlantic Ridge (MAR) at 39° N (Fig. 1). The East Azores Fracture Zone and the MAR intersect at a triple junction[8] in the vicinity of the Azores and the region is marked with (i) a sharp change of trend of the MAR, (ii) the broadening of the ridge into an extensive platform[9] (Fig. 1) and (iii) an unusually high positive regional gravity anomaly[10]. The islands east of the MAR trend obliquely to the proposed plate margins and follow a pronounced bathymetric lineament (Fig. 1), the Terceira Rift[9,11] which extends through parts of Graciosa, Terceira and São Miguel. Krause and Watkins[9] suggest that the Terceira Rift represents a secondary spreading centre trending towards Gibraltar which originated approximately 45 Myr ago.

São Miguel, the largest of the islands, lies near the eastern extremity of the chain 400 km from the MAR crest. Its surface geology is dominated by four large calderas, three of which have erupted during historic times[12] and have produced an extensive blanket of trachytic pumice which covers much of the island[13,14]. Surface rocks range compositionally from alkali basalts to trachytes[15,16] and are exceptionally potassic[17]. We selected a drill site on the gentle flanks of the volcano Agua de Pau which rises to a maximum height of 950 m above sea level and has a diameter at sea level of approximately 15 km. Its surface deposits consist of voluminous trachytic pumice and associated basaltic lavas intercalated with occasional trachytic extrusives. The last recorded eruption from the summit caldera in 1563 AD produced a cover of trachytic pumice and Walker and Croasdale[18] document four similar eruptive events during the past 4,600 years. Agua de Pau must therefore be considered to be currently dormant, as sporadic seismic activity beneath the caldera and a number of boiling hot springs on the flanks also indicate.

Stratigraphy and petrology of the core

Drilling began at 72 m above sea level, but only partial core recovery was possible in the first 148 m because of unconsolidated pyroclastic and mud flow deposits. Below this depth core recovery was virtually continuous to 981 m where drilling terminated following steam production. A synoptic core log is shown in Fig. 2.

Extrusive lavas constitute 72% of the drill core and occur in 140 separate flow units of 4.8 m average thickness and 2.5 m median thickness. Alkali basalts, hawaiites and mugearites predominate and only three trachyte flows (6% of total flow volume) were encountered. In the top 763 m of core a subaerial origin for the flows is suggested by (i) massive nature of flow centres, (ii) complete absence of pillow structures, (iii) intercalation of numerous pyroclastic units lacking any indications of aqueous reworking or stratification, (iv) development of some lateritic horizons, and (v) occurrence of thick vesicular and autobrecciated

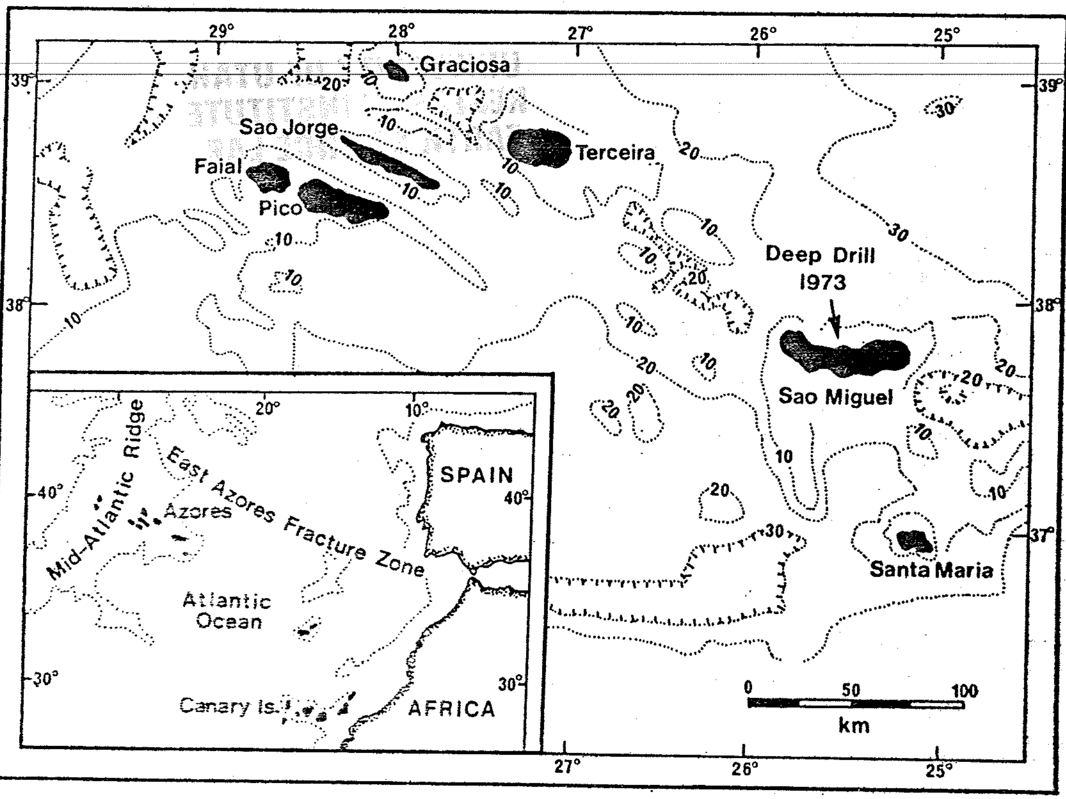

Fig. 1 Location map of Deep Drill 1973. Site coordinates 25° 31.4'W, 37° 48.9'N at 5 km from the caldera wall of Agua de Pau volcano, São Miguel. 1,000 m bathymetric contours are shown[8].

flow tops. Pillowed basaltic rocks with altered glassy margins were first encountered at 880 m where they are found interbedded with massive basaltic flows in a sequence devoid of pyroclastics.

In sharp contrast to the Bermuda drill core[5], intrusives constitute an insignificant fraction in São Miguel. Near vertical basaltic porphyry sheets in chilled contact with basaltic flows were encountered only at 662 m and 738 m.

Pyroclastic deposits, chiefly trachytic in character, account for 22% of the core and range from fine-grained tuffs to pumice deposits, agglomerates and mud flows. Indications of bedding are rare but when seen can be inclined steeply up to 30–40°. Steep depositional dips can also be seen in the recent ash-pumice deposits but these may not be an indication of tectonic tilting since contacts between flow units appeared to be near horizontal over the entire length of the core. Ignimbrite cooling units ranging in thickness from 6 cm to 3.8 m are common in the depth interval 262 m to 508 m. Only two such units have previously been described on the island[17]. Individual pyroclastic units are frequently trachytic in character at the base but grade upward into more basic compositions.

A 107 m thick igneous-sedimentary sequence marks the transition from subaerial to submarine volcanics. Basaltic breccias with a chloritic matrix (altered glass? or ash) are interbedded with massive flows in the upper part of the sequence (Fig. 3) and overlie 15 m of bedded coarse lithic sandstones. One 7 m bed consisting of angular basaltic fragments embedded in a matrix of black lithic sand (carbonate-quartz cemented) is strikingly similar to the black beach sands being formed along the Hawaiian coast line by flows entering the sea (Tilling, personal communication, 1974).

Temperatures

Bottom hole temperatures were monitored during drilling and temperature logs were measured at various intervals after drilling ceased (Fig. 4). The temperatures show 200° C water progressing upward from 550 m at the start to 290 m at the time of the last measurements. The boiling point was exceeded and steam erupted from the hole when the drill rod was removed. The 200° C water would have boiled first when it reached the temperature-pressure boiling curve near 215 m depth. The steps in the last temperature profiles (for example at 110 m, 170 m, and 305 m) were produced by the convection water circulation in the hole because of loose ash sequences in which drill rods enlarged the hole considerably. Convection circulation in the hole is limited upward by tight basaltic and trachytic flows. It was also restricted above 305 m by casing.

Temperatures were nearly constant at 20° to 25° C to 100 m depth, a sudden jump to over 100° C occurred between 100 m and 175 m, then a uniform gradient of about 250° C km^{-1} to a depth of 550 m and finally a very small temperature gradient of less than 10° C km^{-1} to the bottom of the hole (Fig. 4).

In general, temperature profiles in hydrothermal areas show low vertical gradients in permeable rocks where the geothermal heat is carried upward by convection[19]. Impermeable rocks show high gradients since the heat must be carried through them by conduction. The region of this borehole is clearly not a normal hydrothermal system since the generally high porosity (and presumably high permeability) subaerial section above 550 m has a high gradient while the less permeable rocks below 550 m have a very low gradient. We suggest the following model to explain the observed temperatures.

The complete section penetrated by the hole probably does not permit vertical convection. Even though there are extensive permeable rocks (pyroclastics) above 550 m, circulation is restricted by frequent horizontal, impermeable horizons (flows). The lack of cellular convection is seen by the rapid change in measured temperatures with time when convection became possible in the borehole itself. Water flow parallel to the bedding (nearly horizontal), however, is probably not restricted in the permeable pyroclastic horizons. We suggest that there is hot water (205° C) flowing parallel to the bedding at about 550 m and water at 100° C flowing just under the impermeable layer at 110–120 m depth. The hot water probably moves down-dip in these horizons from its source in the upper regions of the volcano. There is no clear evidence for water flow in other

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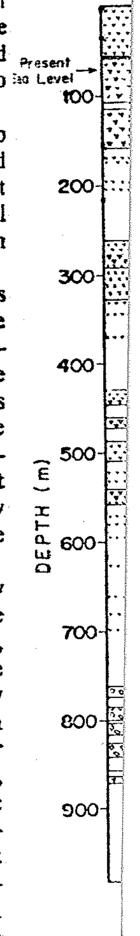

Fig. 2

horizons. The low temperature gradient below 550 m suggests that there is no volcanic heat source directly beneath the drill site itself.

It is difficult to estimate the amount of hot water available in this area for geothermal power since no flow measurements were made. The hole erupted briefly with hot water and steam but was stopped after only 20 min, before any depletion of flow could be detected. The permeability of the core also has not been measured. Large volumes of 200°–210° C water may be available from near 50 m depth if the down-dip flow in the permeable horizons from higher on the volcano is rapid but flow tests are required to confirm this conclusion.

Age determinations

Palaeomagnetic measurements on lava flows in the core indicate that the subaerial, transition and subaqueous sequences are all normally magnetised. This probably indicates magnetisation during the Brunhes polarity epoch, although the possibility of remagnetisation during hydrothermal alteration cannot be discounted. If magnetisation does reflect geomagnetic field polarity the time scale of reversals of polarity of the Earth's magnetic field[20] provides an upper age limit of 0.69 Myr for the formation of the entire volcanic–sedimentary sequence.

Two samples were selected for radiometric dating by the conventional K-Ar method. The first of these, a slightly impure sanidine concentrated from a fresh trachytic flow located at 57 m depth has an apparent age of $(117\pm24)\times10^3$ yr (% $K_2O=6.7$; $^{40}Ar_{radiogenic}/^{40}Ar=0.5$). The second sample, a relatively fresh submarine lava from the 950 m level has an apparent whole rock age of $(280\pm140)\times10^3$ yr (% $K_2O=2.7$; $^{40}Ar_{radiogenic}/^{40}Ar=0.013$). In other words, this rock appears to have retained at least some radiogenic argon in spite of high (~205° C) temperatures encountered. The sample contained $\sim2.5\times10^{-6}$ s.c.c. g^{-1} atmospheric argon; an unusually high value perhaps indicative of exchange of gases between the lavas and overlying hydrothermal sources. We conclude from the radiometric and the magnetic data that the drill core spans a time interval of the order of a few hundred thousand years in the Brunhes normal polarity epoch and that the major vulcanism probably ended about 100,000 years ago.

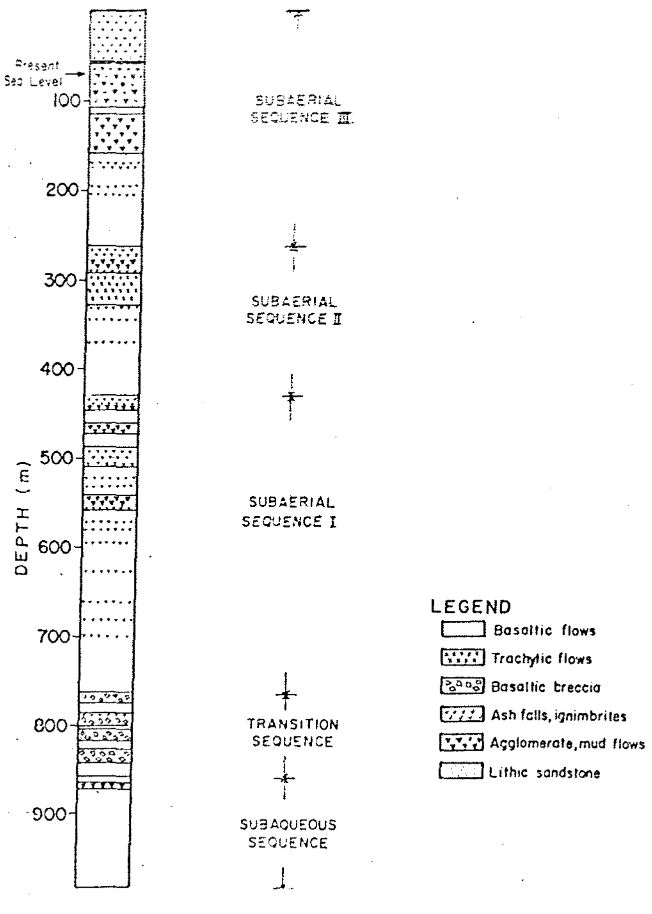

Fig. 2 Log showing major lithologic variations in the São Miguel drill core.

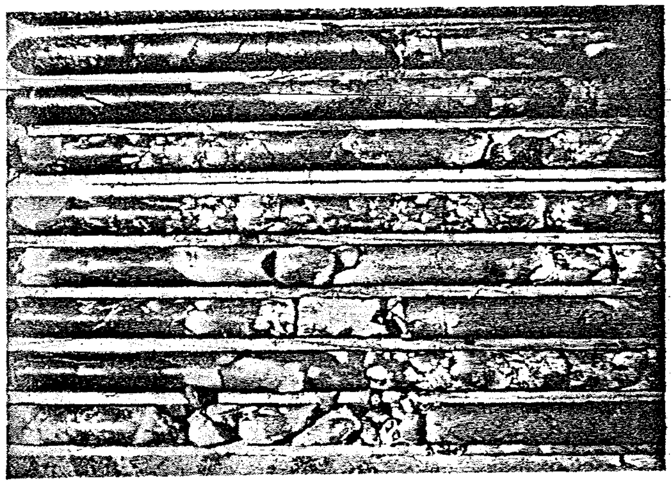

Fig. 3 Breccia from the transition zone consisting of angular basalt fragments of variable size in a matrix of coarse vulcanogenic sand and chloritic material. Basalt fragments show conspicuous leached margins. Length of core segments 0.6 m.

Deep drilling on São Miguel has disclosed several important aspects of the island's geological evolution which are not evident from an examination of its surface geology. Three distinct subaerial eruptive sequences totalling 762 m in thickness were found to overlie a complex 107 m transition zone which documents the changeover from a subaerial to a submarine environment. Each subaerial eruptive sequence commenced with a quiescent phase of basaltic lava extrusion and was followed by increasingly explosive activity. Intercalated tuff beds increase in frequency and thickness and grade into a terminal phase of trachytic pumice deposition with rare trachyte extrusion. Compositional zonation within individual pyroclastic units further supports strong compositional zonation in the magma chamber at this stage. We suggest that each eruptive sequence signals the arrival of a fresh magma batch from depth in the mantle into a shallow magma chamber. Crystal fractionation and possibly assimilation at shallow depth would then yield increasingly differentiated products and an enrichment in volatiles; a combination which would in each case lead to increasingly explosive acidic eruptive activity.

Island subsidence

A surprising result of our experiment has been the depth at which submarine deposits were encountered. Subaerial or shallow marine conditions are found to 786 m below present sea level and indicate substantial subsidence of the island. Postglacial sea level rise since 18,000 BP can account for only 130 m of subsidence[21]. An evaluation of the glacial eustatic control of sea level for the earlier Pleistocene does not seem possible because of the largely unknown influence of tectonic crustal movements on sea level, but is not likely to be much greater. Paleomagnetic and radiometric dating of the core at younger than 0.69 Myr BP yields a minimum average subsidence rate of 0.1 cm yr^{-1}. Other data on the vertical crustal motion in the

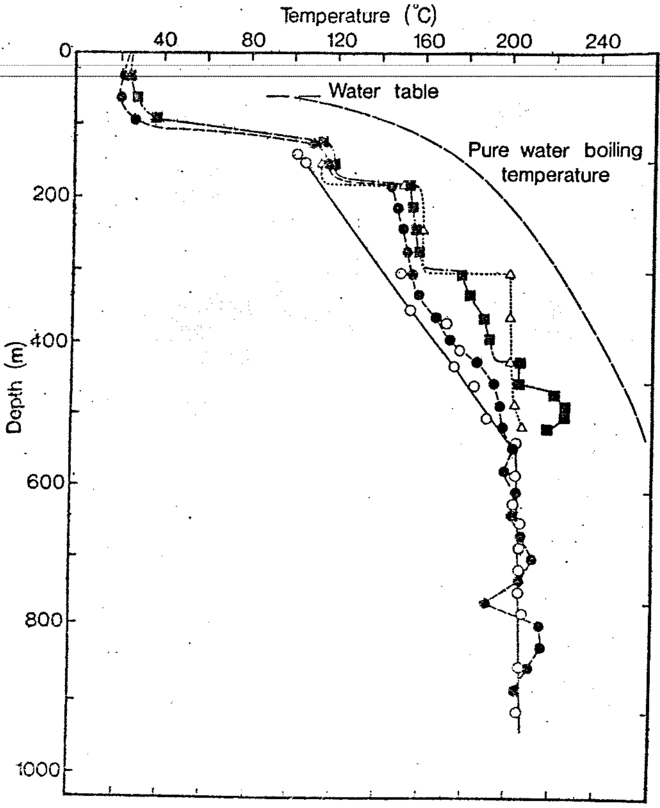

Fig. 4 Temperature measurements with maximum thermometers (±2° C) to 914 m during drilling; to 885 m with thermocouple (±1° C) between 1 and 2 h and again 4 days after termination of water circulation. Two days after further circulation maximum thermometer measurements were made to 518 m. ○: temperatures at the bottom of the hole; temperature logs: ●: 26 August (1–3 h); ■: 2 September (4 d); △: 7 September (3 d).

Azores come from São Miguel's closest neighbour, Santa Maria, where a submarine sequence of basaltic volcanics and sediments of Miocene to Quaternary age is exposed[22]. This implies uplift for the island and suggests that the subsidence of Agua de Pau volcano is a local phenomenon.

The subsidence of ancient oceanic islands to form seamounts has been attributed to the thermal contraction of the lithosphere as it moves away from the spreading centre[23–25], or to the vertical motion of the lithosphere as it slides over a bumpy asthenosphere[26,27]. In either case subsidence rates calculated from known spreading rates or theoretical models yield values of 0.01–0.02 cm yr^{-1} which is an order of magnitude below those observed on São Miguel.

Detailed information on the vertical motion of other active volcanic islands is scarce. An analysis of tide-gauge measurements in the Hawaiian islands[28] reveals recent subsidence rates of 0.5 cm yr^{-1} for Hawaii, 0.2 cm yr^{-1} for Maui, and stable conditions on Oahu. Decreasing subsidence rates correlate with an increase in the geological age of the islands and a decrease in intensity of their recent volcanic activity[29]. Ward[30] has used raised shorelines and drilling data[31] from Oahu to demonstrate that Pliocene subsidence of the island was followed by uplift of 1.6 cm 1,000 yr^{-1} during the Pleistocene.

São Miguel and adjacent Santa Maria exhibit a similar pattern. On Santa Maria, which is undergoing or has undergone emergence, neither historic eruptions nor any hot spring or fumarolic activity are reported. Volcanic activity has been dated to extend back 8.2 Myr[32]. The island is also furthest removed from active spreading centres such as the Terceira Rift. São Miguel, by contrast, shows rapid subsidence, active volcanicity, surface lavas dating from the historic era back to only 4.0 Myr[32], and is situated on the currently active Terceira Rift.

The subsidence of an active volcano like São Miguel arises primarily from crustal loading with the addition of volcanic material. In Hawaii, Swanson[33] believes that simple isostatic adjustment adequately accounts for the observed subsidence. On a simple isostatic model the subsidence of 800 m observed on São Miguel requires the addition of a thickness of about 1 km of subaerial volcanic material to the island and will result in an increase of average elevation of 100–200 m. When a volcanic island becomes extinct, such as Santa Maria, erosion will result in isostatic rebound or uplift. If the top of the submarine section was 800 m below sea level when the island was active, at least 1,000 m has been eroded with a general reduction of elevation of 100–200 m.

Our temperature measurements suggest that the northern flank of Agua de Pau represents a promising prospect for future geothermal exploration. Bottom hole temperatures are well within the range of productive geothermal fields[34] and occur at profitable depth. The thick subaerial volcanic sequence with its high proportion of pyroclastics and thick scoriaceous flow tops provides high porosities and possibly also permeabilities which make high flow rates probable. Further investigations to determine total hot water reserves, possible extraction rates, and the chemistry of the steam and water in this and other wells will be necessary for more specific evaluations. Seismic profiling to evaluate trap conditions near our borehole would seem a sensible next step.

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Observation of tissue metabolites using ^{31}P nuclear magnetic resonance

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P NMR spectra of intact biological tissues can now be observed. The use of the spectra to study the course of reactions within the tissues is illustrated by experiments on muscle and its glycogen particle fraction.

ALTHOUGH phosphorus NMR has only $^1/_{15}$ the sensitivity of proton NMR, it is attractive because studies may be done in aqueous solution and the spectra are relatively simple because of the small number of different chemical environments in which phosphorus atoms are found. In addition, the chemical shift range is much larger for phosphorus than for protons.

As a result of considerable instrumental improvements achieved recently in both the magnitude of the magnetic field and the sensitivity of the detection[1] we are now in a position to study ^{31}P resonances in a large variety of systems at concentrations found naturally in biology, using Fourier transform and impulse response techniques[2]. Useful spectra can now be obtained of systems varying in complexity from solutions of purified enzymes to intact tissues.

Phosphate resonances

At the high magnetic field strength employed (7.5 tesla) the ^{31}P resonances of a large number of biologically important phosphate-containing compounds can be resolved. The chemical shifts of the phosphate groups are in the range of about 30 p.p.m., and many sugar phosphates and glycolytic intermediates can be resolved. Furthermore, the state of ionisation of the phosphates and their interaction with metal ions, such as Mg^{2+}, affect the positions of the resonances. Figure 1 shows ^{31}P spectra of a mixture of compounds recorded at various *p*H values, the individual resonances having been assigned by observing the spectra of the individual components.

The resolution of the resonances from various phosphorus-containing small molecules allows rapid assay of the components of mixtures of these molecules. Measurements are carried out without destruction or dilution of the sample, and provide a method of monitoring turnover and interconversions of these molecules in organelles.

In the glycogen particulate fraction isolated from rabbit muscle, covalent enzyme regulation has been exhaustively studied[3,4] and transient phosphorylation of phosphorylase *b* has been shown to be the principal trigger for glycogen breakdown. The enzymes concerned are also regulated by small ligands. Therefore, knowledge of concentrations of these regulators at any point in the transient covalent activation is important for full understanding of the control mechanism[5]. Figure 2 shows the turnover of the phosphorus containing ligands during a typical transient activation, obtained from a series of ^{31}P NMR spectra, recorded on a single sample. The active form of phosphorylase immediately catalyses glycogen breakdown, leading to the production of glucose-1-phosphate and so (by phosphoglucomutase activity) to glucose-6-phosphate. The production of glucose-6-phosphate is concomitant with phosphate utilisation. During the phosphorylation of phosphorylase *b*, ATP is converted to ADP. Because of the presence of adenylate kinase, which catalyses the reaction $2ADP \leftrightharpoons ATP + AMP$, and of AMP-deaminase, which catalyses the reaction $AMP \rightarrow IMP + NH_3$, the ADP initially formed is depleted and IMP—not distinguishable from AMP by ^{31}P NMR—is produced. The instability of the nucleotide levels indicates that the system is not a very good model for extrapolation to the *in vivo* situation.

The assay technique outlined above has also been used to estimate the separate activities in a crude extract of homogenised rabbit muscle by following the sequential production of glycolytic intermediates. The mass action ratios for some of the

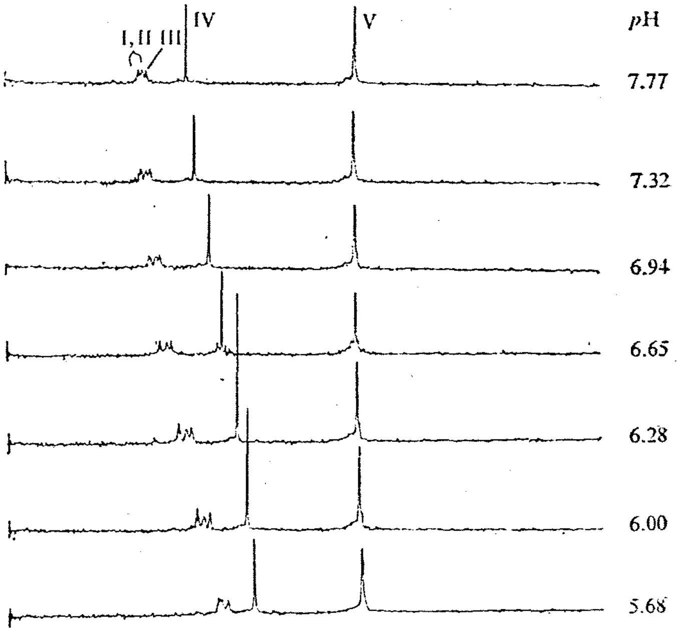

Fig. 1 ^{31}P NMR spectra of a mixture of fructose-1, 6-diphosphate (I, II), IMP (III), inorganic phosphate (IV), creatine phosphate (V) at various *p*H values, recorded at 129 MHz. No buffer present; total phosphate concentration 60 mM. Sweep width 5 kHz, pulse interval 2 s, 200 scans. Spectrum recorded without proton irradiation.