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Environmental Problems of Petroleum Production in the Amazon Lowland of Ecuador *

by

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Summary

The subandean Ecuadorian Amazon lowland, also known as Oriente, is an important petroleum producing region. It forms part of the upper Amazon basin, has a humid tropical climate and an exceptionally rich flora and fauna which is among the most diverse on earth. Its major (northern) part is drained by the Río Napo which joins the Amazon River downstream of Iquitos in Peru. The Oriente slopes down from the Andes, encompassing over 13 million hectares of tropical rain forest which represents 46% of Ecuador's total area.

API gravities of the Cretaceous crude oils in the Oriente region generally range between 10° and 35° API, although the major part of the production is of 26° to 32°. Heavy oils of 10° to 25° are found in the eastern and southern areas of the Oriente basin. Mean daily petroleum production in the Oriente in 1995 was 386,000 barrel, of which 79.5% was produced by the state company *Petroecuador*; companies under service contract with *Petroecuador* and a consortium supplied 20.5%. The production was obtained from a total of 539 wells. The average water content of wet oil is about 35%. The total production of formation waters according to conservative estimates is around 220,000 b/d, of which a small proportion is reinjected.

Following an extensive sampling programme of waste water discharges, oil-contaminated soils, rainforest streams and fresh crude oils, mainly in the fields of *Petroecuador*, a number of inorganic and organic parameters were determined in the laboratory. Laboratory trials were performed to study the patterns of degradation due to bacterial activity in waters and soils and the evaporation behaviour of different crude oils under specific environmental conditions.

Local Oriente creeks affected by formation water discharges close to production facilities, downstream of fresh oil spills and close to unlined waste oil collection pits, show a relatively high conductivity and distinct chemical composition. These rainforest stream water samples reflect mixing of natural surface waters with formation waters (derived from wet oils) at variable volume ratios from 50 to 350. The dominating anion is chloride. The samples also show an ele-

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vated content of barium, manganese, and, to a lesser extent, zinc. Most trace metals of environmental concern are present in the formation waters in relatively low concentrations, and after discharge into local waters are diluted to values which presumably are not harmful to aquatic organisms. This observation does not hold true for selenium, which was detected in formation waters at concentrations of up to 400 μg/L. This element is a strong toxicant to aquatic invertebrates and fish and is methylated biologically in sediments which strongly increases its toxicity.

Water samples taken at a distance of several hundred metres away from open waste oil pits indicate that the liquids collected seep to shallow aquifers nearby. The fact that saline waters penetrate the unlined oil pit walls shows the permeability of the clayey soils. Although the extraction technique used in the present study was unsuitable to determine very low hydrocarbon concentrations in the collected water samples, it appears most likely that water-soluble oil components like monoaromatics leak from the pits, of which at present over a hundred still exist in the Oriente, and contaminate subsurface and surface waters.

Formation waters discharged from installations of the former *Texaco-Petroecuador* consortium, about 170,000 barrel per day, frequently show a visible oil film. Measurements of residual oil content in formation waters sampled from *Petroecuador* production facilities give a mean of 144 mg/L (13 measurements). The values range from 4 mg/L, indicating an optimized separation process, to 706 mg/L, showing a very poor and inefficient treatment. Assuming a mean petroleum content of about 150 mg/L and no polishing of the production discharges, up to 25 barrel or 4000 litres of crude may enter local streams and rivers daily.

Three different crude oils of the Oriente and n-dodecane as a reference substance were studied in a laboratory evaporation experiment at 30 °C. The results show an approximately exponential decrease in weight in the first few days of the experiment (over 20% loss for the lightest oil studied of 30.4 °API) and a slow linear decrease in the following period. The Shuara oil, a heavy crude of 10.3 °API, gave a loss of only 13% in the period of 80 days.

In order to investigate the degradation of crude oil through autochthonous bacteria and fungi, experiments under optimum and deficiency conditions (i.e. nutrient and oxygen limitation) were performed in the laboratory. Biodegradation experiments were undertaken exclusively with native microorganisms from oil-contaminated soils from the Oriente.

Analyses by gas chromatography (GC) of the crude oil residues obtained from the biodegradation trials under optimal conditions show significant microbial utilization of most hydrocarbons, particularly of the n-alkanes (e.g. dodecane and hexadecane). The highest degradation rates were observed in the first 24 hours of the trial and then slowed down until day 5 when concentrations were extremely low. The branched alkanes pristane and phytane, which are much more resistant to biodegradation than the n-alkanes, displayed a rather constant decline in concentration over the five day period. Biological oxidation was minimal under conditions of oxygen and nutrient limitation. The values obtained for these experiments are very close to the control sample, in which all microorganisms were killed at the trial start.

Results obtained for the biodegradation trials in soils are similar to those obtained for water as culture medium although degradation rates are much slower and abiotic losses are greater. Microbial degradation in untreated soil (sampled from the Oriente) was very limited but excellent in the trial series with commercial N-P-K fertilizer added. Preliminary results in the present study show no detectable microbially mediated losses of the monoaromatics, which are known to exhibit poisonous effects over bacteria.

The GC analyses of contaminated soils from spill sites in Oriente oil fields clearly show a fractionation of the different oil compounds during the downward migration in the soil profile. Hydrocarbons of short retention times on the GC column, mainly n-alkanes up to C_{11} and monoaromatics like benzene and its substituted equivalents like isopropylbenzene, are consistently found at much greater depth than the other crude oil components. This mobile and water-soluble fraction is able to migrate through very fine-grained soils of low porosity and may finally reach the groundwater level.

When crude oil is released into the tropical environment through an oil spill, volatile components evaporate, the mobile fraction penetrates into the soil or is washed out via surface run-off, and a variable proportion of oil is metabolized by microorganisms. Finally a bituminous surface layer may form (depending on the quantity of spilled oil) which seals off the fresh crude oil below it and prevents aerobic microbial degradation. Nutrient availability (nitrogen, phosphorus) to the microorganisms in the highly weathered soils of the Oriente generally is very low. The water-soluble fraction of fresh crude oil slowly moves deeper in the soil profile and may persist for decades because of severe oxygen and nutrient limitation to oil-degrading microbes.

Heavy crude oils, which have an increasing share in the total production from the Oriente, consist to a large extent of complex high-molecular weight compounds like asphaltenes and other heterocyclic hydrocarbons which are highly persistent in the environment.

The basic concept in bioremediation of oil-contaminated soils is to stimulate the growth of hydrocarbon-degrading microorganisms by creating optimal conditions for their development through oxygen supply (aeration), sufficient nutrient supply, optimal soil moisture and a not too high concentration of hydrocarbons. A suitable process for soil treatment in the Oriente consists in transfering the contaminated material to lined pits of 40-50 tons capacity, where it is mixed with organic compost and woodchips (can be replaced by coffee shells or rice ash), supplemented with agricultural nitrogen-phosphorus-potassium fertilizer, and the mixture kept moist. Continuous aeration by tilling of the material in regular periods is necessary.

Results show that the autochthonous (indigenous) bacteria and fungi of the Oriente have a high biodegrading capacity for most hydrocarbon components. We conclude that the use of allochthonous (exotic) bacterial cultures in bioremediation measures in the Oriente will not show better results than the degradation by native microorganisms which already are present in sufficient concentrations at oil-polluted sites.

Besides the pollution of soils, water and air linked to petroleum development, affecting both indigenous inhabitants and colonists, it is the loss of rainforest habitats which threatens fauna and flora, and the social and cultural integrity of indigenous forest dwellers.

A review of available data on deforestation related to petroleum production in the Ecuadorian Amazon lowland underlines the fact that the infrastructure requirements of the petroleum industry (roads, pipelines) cause the biggest ecological problems. Modern technology in exploration and production, environmentally conscious management and innovative concepts for oil operations in rainforests are recommended in the closing chapter to reduce the environmental impact of crude oil production in the Oriente.

Resumen

Las tierras subandinas de la Amazonia Ecuatoriana, también conocidas como Oriente, son una importante región productora de petróleo. Forman parte de la cuenca Amazónica alta, tienen un clima húmedo tropical y una excepcional riqueza en flora y fauna que es una de la más diversa en el mundo. La parte más extensa (norte) está avenada por el río Napo, afluente del río Amazonas con el que se une río abajo de Iquitos, en Peru. El Oriente se extiende desde las laderas orientales de los Andes y comprende más de 13 millones de hectáreas de bosques tropicales que representan el 46% del area total del Ecuador.

La gravedad API de los crudos del cretáco en el Oriente varian entre los 10° y 35° API, pero la mayor parte de la producción de petróleo está entre los 26° y 32°. Los crudos pesados de 10° a 25° API se encuentran en la parte este y sur de la cuenca oriental. El promedio diario de la producción petrolera en el Oriente en 1995 fue de 386,000 barriles, de los cuales el 79.5% fue producido por la compañía estatal *Petroecuador*; compañias y consorcios bajo contrato de servicio con *Petroecuador* suministran el 20.5% restante. La producción proviene de un total de 539 pozos. El contenido de agua en el crudo es de aproximadamente 35%. La producción total de las aguas de formación de acuerdo a datos estimados es de alrededor de 220,000 barriles/día, de los cuales una pequeña proporción es reinyectada en los pozos.

Siguiendo un intensivo programa de muestreo principalmente en los campos de *Petroecuador*, se determinaron en el laboratorio un número relevante de parámetros inorgánicos y orgánicos en aguas de descargas de producción, suelos contaminados con crudo, corrientes de agua de la zona y petróleo fresco. Pruebas de laboratorio fueron establecidas para estudiar la degradación debida a la actividad bacteriana en aguas y suelos y la capacidad de evaporación de diferentes crudos bajo condiciones específicas.

Los riachuelos del Oriente afectados por las descargas de las aguas de formación cercanos a las instalaciones

de producción, río abajo de los derrames de crudo fresco y cerca a los pozos de recolección de petróleo crudo, muestran una relativamente alta conductividad y una composición química distinta. Las muestras de estos riachuelos demuestran una mezcla de las aguas superficiales naturales con las aguas de formación (proveniente del petróleo bruto) en proporción de volumen entre 50 y 350 veces. El anión dominante es el cloruro. Estas muestras también tienen un contenido elevado de bario, manganeso, y en menor concentración, zinc. Muchos metales que influyen en el medio ambiente están también presentes en las aguas de formación en concentraciones relativamente bajas, que luego son descargadas en las aguas locales y diluidos a valores que presumiblemente no son daniños para los organismos acuáticos.
Esta observación no es verdadera para el selenio, que fue detectado en aguas de formación en concentraciones sobre los 400 µg/L. El selenio es fuertemente tóxico para los invertebrados acuáticos y peces y es biológicamente metilado en los sedimentos, lo cual incrementa su toxicidad.

Muestras de aguas tomadas a una distancia de varios cientos de metros lejos de los pozos de producción y de las piscinas de desechos, indican que los liquidos recolectados se filtran hacia los acuíferos cercanos. El hecho de que las aguas salinas penetran las paredes, demuestra la permeabilidad de los suelos arcillosos. A pesar de las técnicas de extracción usadas en este estudio, no fueron suficientes para determinar las bajas concentraciones de hidrocarburos presentes en las muestras de agua recolectadas, aparece que componentes del petróleo solubles en agua tales como los monoaromáticos filtran de las piscinas (de las cuales existen actualmente más de 100 en el Oriente) y contaminan el subsuelo y las aguas superficiales.

Las aguas de formación descargadas de las instalaciones del ex-consorcio *Texaco-Petroecuador*, alrededor de 170,000 b/d, muestran frecuentemente una película de aceite visible. Medidas de los residuos de petróleo contenidos en las aguas de formación de las instalaciones de *Petroecuador*, dan un promedio de 144 mg/l (13 mediciones). El valor más bajo medido de 4 mg/l indica un proceso óptimo de separación, y el máximo de 706 mg/l un tratamiento muy deficiente. Se puede asumir que en la producción de petróleo se descargan alrededor de 150 mg de crudo por litro de agua de formación que equivaldrían (como valor máximo) a 25 barrel ó 4000 litros de crudo que pueden entrar cada día en los riachuelos y ríos de la región.

Tres diferentes crudos del Oriente y n-dodecano como sustancia de referencia, fueron estudiados en un experimento de evaporación en el laboratorio a 30° C. Los resultados demostraron una disminución exponencial en el peso del crudo en los primeros días (más del 20% de pérdida en el crudo más liviano estudiado de 30.4° API) y una ligera disminución linear en el siguiente período. El crudo pesado del campo Shuara (10.3° API), tiene una pérdida solamente de 13% en un período de 80 días.

Para investigar la degradación del petróleo por bacterias y hongos autóctonos se realizaron experimentos bajo condiciones óptimas y deficientes (limitación de nutrientes y oxígeno) en el laboratorio. Los ensayos de biodegradación fueron realizados exclusivamente con microorganismos nativos provenientes de los suelos contaminados con petróleo del Oriente.

Análisis por cromatografía de gases (CG) de los crudos residuales obtenidos en los experimentos de biodegradación bajo condiciones óptimas, muestran una significativa utilización microbiana de muchos hidrocarburos, particularmente de los n-alcanos (e.g. dodecano y hexadecano). Altas velocidades de degradación se observaron en las primeras 24 horas de los ensayos y luego, disminuyeron hasta el quinto día, en donde las concentraciones fueron extremadamente bajas. Los alcanos ramificados pristano y fitano, los cuales son mucho más resistentes a la biodegradación que los n-alcanos, presentan una ligera disminución constante de la concentración en el período de 5 días. La oxidación biológica fue mímima bajo las condiciones limitantes de oxígeno y nutrientes. Los valores obtenidos para estos experimentos son muy cercanos a los de la muestra de control, en la cual todos los microorganismos fueron eliminados al inicio del ensayo.

Los resultados obtenidos para los ensayos de biodegradación en suelos son similares a aquellos obtenidos en agua como medio de cultivo, a pesar de que la velocidad de degradación es mucho más baja y las perdidas abióticas son mayores. La degradación microbiana en suelos (tomados del Oriente) fueron muy limitadas pero por el contrario, fueron excelentes en la serie de ensayos con fertilizante N-P-K (nitrógeno-fósforo-potasio) añadido. Resultados preliminares en este estudio demuestran de que no hay pérdidas microbianas de los monoaromáticos, los cuales son conocidas por exhibir efectos nocivos sobre las bacterias.

Los análisis por CG de suelos contaminados por derrames de crudo en el Oriente, muestran claramente un fraccionamento de los diferentes compuestos del crudo durante su migración en el suelo. Hidrocarburos con cortos tiempos de retención en la columna de CG, principalmente los n-alcanos de hasta 11 átomos de carbono y monoaromáticos como el benceno y sus equivalentes sustituidos como el isopropilbenceno, se encuentran consistentemente a mayor profundidad que los otros componentes del crudo. Esta fracción móvil y soluble en el agua, son capaces de migrar a través de suelos de grano muy fino y de baja porosidad, y pueden finalmente alcanzar el nivel de las aguas subterráneas.

Cuando un derrame de crudo ocurre en un ambiente tropical, se evaporan los compuestos volátiles, la fracción móvil penetra en el suelo o es arrastrada por el agua en la superficie, y una proporción variable de crudo es metabolizada por los microorganismos. Finalmente se forma una capa bituminosa en la superficie (dependiendo de la cantitad de crudo derramado) tapando herméticamente el petróleo fresco por debajo y impidiendo la degradación microbiana aeróbica. La disponibilidad de nutrientes (nitrógeno, fósforo) para los microorganismos en los suelos ferralíticos del Oriente generalmente es escasa. Cuando un petróleo fresco penetra en el suelo, la fracción soluble en agua se mueve lentamente hacia dentro de la tierra y puede persistir por décadas sin ser degradado por los microorganismos debido a la limitación de oxígeno y nutrientes.
Los crudos pesados, actualmente con un incremento constante en la producción total en el Oriente, consisten de moléculas complejas de alto peso molecular tales como los asfaltenos e hidrocarburos heterocíclicos los cuales persisten en el medio ambiente.

El concepto básico en la bioremediación de suelos contaminados de petróleo es la de estimular el crecimiento de microorganismos que degradan los hidrocarburos, creando las condiciones óptimas para su desarrollo a través de oxigenación (aeración), suministro de suficientes nutrientes, mantenimiento de la humedad óptima del suelo a tratar, y una concentración de hidrocarburos no muy alta. Un proceso apropiado para tratamiento de suelos en el Oriente consiste en la transferir el material contaminado a piscinas de 40 a 50 toneladas de capacidad, en donde se mezclan con abono orgánico y aserrín (podría ser reemplazado por cáscara de café o ceniza de arroz) suplementado con fertilizante agrícola (N-P-K) y manteniendo la mezcla húmeda. Es necesario voltear el material en períodos regulares para dar una aeración continua.

Los resultados muestran que las bacterias y hongos autóctonas (nativas) del Oriente, tienen una gran capacidad de biodegradación para la mayoria de los hidrocarburos. Podemos concluir que el uso de cultivos de bacterias no autóctonas (exóticas) en la bioremediación en el Oriente, no dan mejores resultados que los microorganismos nativos que están siempre presentes en suficientes concentraciones en los lugares contaminados con crudo.

Luego, la contaminación de suelos, aguas y aire debido al desarrollo petrolero es un problema predominante para los habitantes de la región, colonos e indígenas. Pero es la pérdida del habitat del bosque húmedo que amenaza la fauna and flora, y la integridad social y cultural de los pueblos indígenas viviendo en el bosque. Una revisión de los datos de la deforestación relacionada a la producción petrolera en la Amazonia Ecuatoriana como efecto de los requerimientos de la infraestructura petrolera (carreteras, caminos, oleoductos) demuestran que esta es la causa del mayor problema ecológico.
Es recomendable una tecnología moderna en exploración y producción, un manejo conciente del medio ambiente y conceptos innovadores para la operación petrolera en bosques tropicales para reducir el impacto ambiental de la producción de petróleo en el Oriente.

Zusammenfassung

Das subandine Amazonastiefland Ecuadors, der Oriente, ist eine wichtige erdölproduzierende Region. Seine Fläche beträgt über 13 Millionen Hektar tropischen Regenwaldes, die 46 Prozent der Gesamtfläche Ecuadors darstellt. Der Oriente gehört zum oberen Einzugsgebiet des Amazonas, hat ein feuchttropisches Klima und zählt mit seiner außerordentlich reichhaltigen Flora und Fauna zu einer der Regionen mit der höchsten Biodiversität weltweit. Der größte Teil des Oriente gehört zum Einzugsgebiet des Río Napo, der kurz unterhalb Iquitos in Peru in den Amazonas mündet.

Die geförderten kretazischen Erdöle liegen generell zwischen 10° und 35° API-Schweregraden, der Großteil der Produktion allerdings bei 26° bis 32°. Schwere Öle von 10° bis 25° API finden sich in den östlichen und südöstlichen Bereichen des Oriente-Bekkens. Die mittlere tägliche Rohölproduktion aus dem Oriente betrug 386.000 Barrel im Jahr 1995, von denen 80 Prozent von der staatlichen Erdölfirma *Petroecuador* und der Rest von privaten ausländischen Firmen gefördert wurden. Die Förderung stammte 1995 aus insgesamt 539 Produktionsbohrungen. Der durchschnittliche Wassergehalt des geförderten Naßöls beträgt etwa 35 Prozent. Die Gesamtförderung an Formationswässern lag bei etwa 220.000 Barrel pro Tag, von denen ein geringer Teil wieder verpreßt wurde.

Nach einer umfangreichen Probenahme von Produktionsabwässern, natürlichen Wässern, ölkontaminierten Böden und frischen Rohölen, vornehmlich in den Feldern von *Petroecuador*, wurde eine große Anzahl von anorganischen und organischen Parametern im Labor bestimmt. Zur Untersuchung des Abbauverhaltens von Rohöl wurden Laborversuche zum mikrobiellen Abbau und zum Verdunstungsverhalten mit verschiedenen Ölen unter spezifischen Umweltbedingungen durchgeführt.

Fließgewässer im Oriente, die durch Einleitung von Produktionsabwässern belastet sind, weisen eine relativ hohe elektrische Leitfähigkeit und eine deutlich andere chemische Zusammensetzung auf als natürliche Schwarzwässer des amazonischen Regenwaldes. Das gleiche gilt für Wasserläufe stromabwärts von frischen Ölunfällen und in der Nähe von Erdbecken zum Sammeln von Abfallölen. Die berechneten Mischungsverhältnisse von natürlichen Wässern mit Formationswässern (aus dem Naßöl) in den beprobten Wasserläufen betragen zwischen 50 und 350. Chlorid ist das dominierende Anion. Spurenmetalle wie Barium, Mangan und Zink treten ebenfalls in deutlich erhöhten Konzentrationen auf. Die meisten in den Formationswässern enthaltenen Schwermetalle treten in relativ geringen Gehalten auf und werden nach Einleitung in lokale Fließgewässer rasch auf Werte verdünnt, die vermutlich für Wasserlebewesen nicht schädlich sind. Eine Ausnahme bildet jedoch das Selen, das in Formationswässern in Gehalten von bis zu 400 μg/l gemessen wurde. Selen ist für aquatische Invertebraten und Fische hochgiftig und wird in Sedimenten biologisch methyliert, wodurch seine Toxizität weiter zunimmt.
Wasserproben, die mehrere Hundert Meter von offenen, nicht abgedichteten Erdölsammelbecken entfernt genommen wurden, zeigen an, daß die wäßrigen Anteile der gesammelten Naßöle durch das Erdreich sickern und nahegelegene Gewässer belasten. Die Tatsache, daß hochsaline Wässer die Wände der Erdbekken durchdringen, weist auf die Permeabilität der tonigen, lateritischen Böden hin. Die in dieser Studie verwendete Extraktionsmethode war ungeeignet zur Bestimmung sehr geringer Kohlenwasserstoffkonzentrationen in Wässern. Es ist aber anzunehmen, daß auch wasserlösliche Bestandteile des Erdöls wie etwa die Monoaromaten von den Ölbecken, von denen es noch über 100 im Oriente gibt, in Grund- und Oberflächengewässer gelangen.

Formationswässer, etwa 170.000 Barrel pro Tag, die von den Produktionsanlagen des ehemaligen *Texaco-Petroecuador*-Konsortiums abgeleitet werden, weisen häufig einen sichtbaren Ölfilm auf. Die Bestimmung des Restölgehaltes in Aufbereitungsabwässern aus Anlagen von *Petroecuador* ergab einen Mittelwert von 144 mg/L (13 Messungen). Die Werte liegen zwischen 4 mg/L, was einen optimierten Abscheidungsprozeß belegt, bis zu 706 mg/L, was auf einen sehr mangelhaften Trennungsprozeß hinweist. Unter Annahme eines mittleren Restölgehaltes von 150 mg/L und keiner weiteren Aufbereitung der Abwässer ergibt sich eine Menge von 25 Barrel oder 4.000 Litern Rohöl als Maximalwert, die auf diese Weise jeden Tag in die lokalen Fließgewässer gelangen.

Für die Verdunstungsversuche bei 30°C im Labor wurden drei verschieden schwere Öle des Oriente und n-Dodekan als Referenzsubstanz verwendet. Die Ergebnisse zeigen eine annähernd exponentielle Gewichtsabnahme während der ersten Tage des Experiments, über 20 Prozent für das leichteste Öl mit 30,4° API, und eine langsame lineare Abnahme für die restliche Versuchslaufzeit. Für das schwerste Öl (10,3° API) ergab sich nach 80 Tagen nur ein Verlust von 13 Prozent.

Zur Untersuchung des Rohölabbaus durch autochthone Bakterien und Pilze wurden Laborversuche sowohl unter Optimal- als auch Mangelbedingungen (nährstoff- und sauerstofflimitiert) durchgeführt. Die Abbauversuche wurden ausschließlich mit natürlichen Mikroorganismen angesetzt, gewonnen aus ölbelasteten Boden aus dem Oriente. Die Analyse mittels Gaschromatographie (GC) der Ölrückstände aus der Versuchsreihe unter Optimalbedingungen zeigen einen deutlichen Abbau der meisten Kohlenwasserstoffe an, insbesondere der n-Alkane. Die Abbaurate war in den ersten 24 Stunden des Versuchs am höchsten und sank dann deutlich bis zum Versuchende am 5. Tag, bei sehr niedrigen Restkonzentrationen, ab. Die verzweigten Alkane Pristan und Phytan, die gegenüber den n-Alkanen erheblich langsamer angegriffen werden, wiesen über die Versuchsdauer von fünf Tagen eine relativ gleichmäßige Konzentrationsabnahme auf. Die mikrobielle Oxidation war minimal bei Abwesenheit von Sauerstoff oder Nährstoffen (Spurenelementen). Die für diese Versuchsreihe ermittelten Restkonzentrationen an Erdöl lagen sehr nahe an dem Kontrollversuch, in dem die Mikroorganismen zu Versuchsbeginn abgetötet worden waren.

Die Versuche zum mikrobiellen Abbau in Böden zeigten in der Tendenz die gleichen Ergebnisse, nur waren die Abbauraten ingesamt niedriger und die abiotischen Verluste (durch Verdunstung) höher. Der mikrobielle Abbau in unbehandeltem, natürlichem Boden aus dem Oriente war sehr gering, jedoch in der Versuchsreihe mit Zugabe von handelsüblichem N-P-K-Dünger sehr hoch. Vorläufige Ergebnisse der vorliegenden Studie zeigen keinen nennenswerten biologischen Abbau von Monoaromaten, von denen bekannt ist, daß sie auch für Mikroorganismen toxisch sind.

Die GC-Analysen von Extrakten kontaminierter Böden von Ölunfällen zeigen deutlich, daß während des Eindringens des Rohöls in tiefere Bodenschichten eine Auftrennung der verschiedenen Ölbestandteile stattfindet. Kohlenwasserstoffe mit kurzen Retentionszeiten auf der GC-Säule, vornehmlich n-Alkane mit weniger als elf Kohlenstoffatomen und Monoaromaten wie Benzol und seine substituierten Verbindungen wie Isopropylbenzol, wurden in den untersuchten Bodenprofilen stets in größeren Tiefen angetroffen als die übrigen Ölkomponenten. Diese mobile und z.T. wasserlösliche Fraktion vermag durch sehr feinkörnige Böden von geringer Porosität zu migrieren und kann so schließlich den Grundwasserspiegel erreichen.

Wird Rohöl durch einen Ölunfall freigesetzt, verdunsten die leichtflüchtigen Bestandteile, die mobile Fraktion dringt in den Boden ein oder wird oberflächlich ausgewaschen, und ein gewisser Anteil wird von Mikroorganismen metabolisiert. Schließlich bleibt an der Oberfläche eine bitumenartige Schicht zurück (abhängig von der Menge des ausgelaufenen Öls), der das frische Rohöl darunter versiegelt und den mikrobiellen aeroben Abbau verhindert. Die Nährstoffverfügbarkeit für die Mikroorganismen in den hochgradig verwitterten Lateriten der Region ist sehr gering. Der wasserlösliche Anteil von frischem Öl wandert im Bodenprofil tiefer und kann dort für Jahrzehnte unter Bedingungen starker Spurenelement- und Sauerstofflimitierung für die ölabbauenden Organismen verbleiben.

Schwere Rohöle, die einen zunehmenden Anteil an der Rohölförderung im Oriente haben, bestehen zu einem hohen Prozentsatz aus komplexen Verbindungen mit hohem Molekulargewicht wie Asphaltene und anderen heterocyclischen Kohlenwasserstoffen, die kaum mikrobiell abgebaut werden und daher sehr persistent sind.

Das der biologischen Sanierung von ölbelasteten Böden zugrundliegende Prinzip besteht darin, das Wachstum von ölabbauenden Bakterien zu fördern, indem optimale Bedingungen für ihre Entwicklung geschaffen werden. Dies geschieht durch Belüftung des Bodens (Sauerstoffzufuhr), ausreichende Nährstoffversorgung, optimale Bodenfeuchte und Einhaltung einer nicht zu hohen Kohlenwasserstoffkonzentration zu Beginn. Ein geeignetes Verfahren zur Bodenbehandlung im Oriente besteht darin, das ölkontaminierte Material in abgedichtete Becken mit einer Kapazität von 40-50 Tonnen zu verbringen, mit Kompost und Holzspänen (auch Kaffeeschalen oder Reisasche) zu mischen, mit handelsüblichem Stickstoff-Phosphor-Kalium-Dünger zu versetzen, und die Mischung feucht zu halten. Umpflügen des Ölbeetes in regelmäßigen Abständen stellt die gleichmäßige Belüftung sicher. Die Ergebnisse zeigen, daß die autochthonen Bakterien und Pilze eine hohes Abbauvermögen für die meisten Rohölkomponenten aufweisen. Die Verwendung von Kulturen allochthoner (exotischer) Mikroorganismen zur Beschleunigung des Abbauprozesses wird sehr wahrscheinlich nicht zu besseren Abbauleistungen führen als die Metabolisierung der Kohlenwasserstoffkomponenten durch die Organismen, die natürlicherweise in den ölkontaminierten Böden des Oriente in ausreichender Zahl auftreten.

Während die von der Erdölförderung verursachte Verschmutzung von Böden, Gewässern und der Luft vor allem ein Problem für die Bewohner der Region darstellt, sowohl Indigene als auch Siedler aus anderen Landesteilen, so ist es der Verlust des Habitates Regenwald, der die Flora und Fauna und die soziale und kulturelle Integrität von indigenen Waldbewohnern am stärksten bedroht.

Die Auswertung von verfügbaren Daten zum Waldverlust im ecuadorianischen Amazonasgebiet, der in direkter und indirekter Beziehung zur Erdölförderung steht, unterstreicht die Tatsache, daß die für die Ölproduktion erforderliche Infrastruktur wie Straßen und Ölleitungen die größten ökologischen Probleme verursacht.

Moderne Technik zur Erschließung und Förderung, umweltbewußtes Management und innovative Konzepte zur Ölgewinnung in ökologisch sensiblen Regenwaldgebieten werden als Empfehlungen am Schluß der Studie beschrieben, um die Umweltauswirkungen der Rohölförderung im Oriente zu minimieren.

Foreword

by Elizabeth Dowdeswell, Executive Director, United Nations Environment Programme

Petroleum exploration and exploitation, like other natural resource extraction activities, can have strong impacts on the environment. Such activities as clearance of forests for seismic surveys and oil field development facilities such as well rigs, pipelines, access roads and field camps (in the exploration phase), accidental oil spills, leakage of tanks and pipework, and pumping of saline formation waters (during production), are a few examples of such impacts.

Even in a well-managed operation, significant environmental damage still can occur, especially in difficult terrain in the humid tropics. Thus, the manner in which petroleum companies approach their operations can significantly affect the ultimate environmental damage likely to result from such activities. Modern technology to reduce environmental impacts like water pollution is available as are management and regulatory tools, such as Environmental Impact Assessment and Environmental Auditing. Application of such techniques and tools in petroleum extraction clearly will work to minimize potential environmental damage, and benefit society at large.

It also is clear that the impact of petroleum exploitation is not limited to the physical environment. Account has also to be taken of lost resources and livelihoods for indigenous people. Destroyed forests and polluted waterbodies can strongly affect hunters and gatherers, not only in the upper catchment of the Amazon river, the study area of this project, but downstream as well. Indeed, avoidance of conflicts between neighbouring communities may require that related environmental damage be acknowledged and compensated properly.

Within the context of sustainable development, UNEP's interest in petroleum exploitation stems from several factors. The first is that crude oil production is a very important economic activity, both in industrialized and developing countries. In industrialized countries, petroleum production, like other extractive industries, is under relatively strict regulation from supervisory bodies, requiring that external environmental costs to society be adequately addressed. In contrast, the situation often is different in developing countries. Those countries frequently lack strong regulatory frameworks and enforcement capabilities, economic incentives, and other effective environmental management tools for dealing with the impacts of petroleum production. Capacity building regarding the environmental ramifications of such issues remains a major UNEP activity.

A second rationale is that pollution and other environmental and social problems related to petroleum exploitation often go beyond purely technical issues. In regard to water resources, they can result in conflicts between various user groups. When international waters are concerned, even larger-scale conflicts can result. The Amazon is an international river, and severe petroleum pollution in one of its major upstream tributaries like the Río Napo could potentially affect the downstream countries Peru and Brazil.

Since its inception, UNEP has worked to foster regional cooperation between riparian countries sharing international water systems.

In addition to producing guidelines for mining and extraction activities, including petroleum exploitation, the United Nations System worked to facilitate preparation and adoption in 1992 of the 'Berlin Guidelines' on mining. These guidelines stipulate good management practices, noting that "best practices, even in the absence of environmental regulations, should be applied". Similar views were repeated at the Rio Conference, and were included in 'Agenda 21' as well.

The visit of the UNEP study team in November 1995 to oil fields in Ecuador's upper portion of the Amazon River drainage basin was a very encouraging exercise. It highlighted interest and commitment not only by the Government of Ecuador through its *Dirección Nacional de Hidrocarburos*, but also by the major petroleum companies engaged in the region.

The main subject of the study described herein, was the fate of crude oil, i.e. its biodegradation and evaporation, after being released into the environment as a result of accidental oil spills and discharges of production waters. Its primary purpose is to present the findings of this study to a wide audience, particularly decision-makers (e.g. governmental-level regulators of the petroleum industry), scientists, engineers and professionals in related fields, and the public at large, in the hope of providing guidance regarding the environmental consequences of, and reactions to, such occurrences.

One other item of interest in regard to this study is the new approach for minimizing environmental and social impacts of petroleum operations, developed by the U.S. firm *ARCO International* for use in its Ecuadorian oil concession. This approach attempts to minimize the 'footprints' left in the Amazonian rainforest by petroleum development.

As a source of further information on practical methods and measures to minimize the impacts of crude oil production, it is included as an annex to this document.

In conclusion, it is my sincere hope that this study will contribute significantly to the preservation and protection of the Amazonian environment, whose vast natural resources are increasingly being tapped to enhance economic development of this region.

EDowdeswell

Elizabeth Dowdeswell
Executive Director

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ANEXOS

1. Introduction

The United Nations Environment Programme (UNEP) has commissioned the *Technische Universität Clausthal* to conduct a study in cooperation with the *Escuela Politécnica Nacional* and *Technische Universität Berlin* on selected aspects of freshwater pollution, and to identify other significant environmental impacts caused by the production of crude oil in the Amazon region (the *Oriente*) of Ecuador. The study is being executed in coordination with *Dirección Nacional de Hidrocarburos, Petroecuador, Petroproducción*, and other Ecuadorian government institutions and private oil companies.

The main objective is to investigate the fate of crude oil and highly saline formation waters which enter the tropical environment through production facility discharges and accidental oil spills. An extensive literature review has shown that very little information exists on this problem.

The weathering of oil is mainly dependent on two processes: evaporation and biodegradation mediated through bacteria and fungi. In laboratory trials, we have investigated the degradation due to bacterial activity, evaporation and dissolution of soluble constituents of different crude oils in waters and soils under specific environmental conditions. Following an extensive sampling programme, mainly in the fields of *Petroproducción*, laboratory work was undertaken to determine some relevant inorganic and organic parameters in samples of waters and soils from waste discharges, oil spills, natural waters and fresh crude oils.

2. Sampling, Experimental Design and Analytical Methodology

2.1. Sampling

Waters. Water samples (gulp samples taken by hand 20-50 cm below the water surface) were collected from watercourses in and around the areas of petroleum production, in the vicinity of fresh spills, and close to waste discharges from production facilities (process waters). Water temperature, pH, conductivity and oxygen content were measured in the field using portable electronic equipment.

The formation waters analyzed were sampled from the "wash tank" in the central production facilities in which the produced crude oil is treated with chemicals in order to break the oil-water emulsion and separate the two liquids.

Samples for cation and anion analysis were taken in 100 mL or 250 mL acid-washed polyethylene PE bottles. In order to analyze any petroleum compounds present, water samples (1-2 L) were extracted with cyclohexane in a relation 1:20 in 1 L separatory funnels. The organic solvent extract was submitted to gas chromatography analysis.

Soils contaminated with crude oil. In order to determine the *in situ*-weathering of crude oil, the uppermost 2-5 cm of the soil profile from dateable oil spills were sampled. The penetration depth of oil in the soil and its biodegradation were determined on the same sites. A manual drill corer was used to take samples every 10-20 cm in the soil profile down to a depth of 2 m. The samples were collected in glass vials of 50 mL with PTFE lids and preserved with a 2% solution of sodium azide to kill microorganisms. Soil samples were extracted with cyclohexane using a Soxhlet apparatus. The filtered extract was submitted to GC analysis.

2.2. Laboratory Experiments

Determination of oil evaporation. Due to logistical constraints and better practicability, it was decided to perform evaporation trials in the laboratory and not in the field. In order to simulate the climatic conditions of the Oriente, a closet of about 2 m^2 (height 2 m) with insulated walls was constructed. A temperature of 30 °C was maintained with the help of an electric heating fan. Humidity was kept high using buckets filled with water located in the closet.

The experiment was performed for the duration of 110 days with oils collected from three different Oriente oil fields: Sacha and Shushufindi oils (median crudes) and Shuara well #27 (heavy crude). One litre of each oil was poured into shallow troughs made of steel (cake moulds). The specific gravity was determined before the experiment began: an empty 1 L glass cylinder was tared. 1 L of crude was poured into the cylinder and the weight was determined again. The loss due to evaporation of volatile components was determined gravimetrically in appropriate time intervals. Measurements were made daily (in the beginning) and every 3-4 days for the rest of the experiment.

n-dodecane submitted to the same conditions was used as a reference substance. The oils were sampled at appropriate intervals for GC analysis.

Microbial degradation trials in aqueous medium. In order to investigate the degradation of crude oil by autochthonous bacteria and fungi, experiments under optimum and deficiency conditions were performed in the laboratory. Kinetics of biodegradation, selectivity and extent of degradation were the objectives to be investigated.

The first step was to obtain a broth of bacterial culture which was used to inoculate the experiments. One litre of distilled water was filled in a 1.5 L Erlenmeyer flask. Nutrient salts (phosphates, nitrates, potassium, trace elements) according to Behrendt (1994) were added. One mL of fresh crude was added to about 10 g of oil contaminated soil, containing native bacteria, sampled from a spill in the Sacha field (Oriente). Oxygen was applied with an electric air pump. 1 mL of oil was added every day. Within a few days, a microbial culture broth developed.

The proper biodegradation trials were performed using 500 mL glass bottles with PTFE screw lids. 100 mL of distilled water and 0.1 mL of crude oil were mixed with 2 mL of the bacterial broth. Trials were performed under:

A. optimum conditions (addition of nutrients and oxygen)

B. deficiency conditions without nutrient addition

C. deficiency conditions without oxygen addition

D. control: like A) but bacteria were killed with 2% sodium azide solution

For the experiments A, C and D, nutrients according to Behrendt (1994) were added. The triple quantity of oxygen gas was applied (1.5 L) to ensure a pure oxygen atmosphere, and the bottles were closed tightly. In the case of trial series C, the bottles were closed after filling and opened only at the end of the experiment.

Trials were performed at 30 °C. Homogenisation of the solutions was achieved using an agitated water bath or a shaking table. The duration of the trials was five days. Bottles were opened every 12 hours and oxygen was added in the series A, B and D. The addition of oxygen gas from a pressurized bottle inevitably resulted in the stripping of volatile petroleum components from the flasks.

Every 24 hours a bottle was removed from each trial series and the solution submitted to extraction. For the four trial series of five day duration, a total of 20 bottles was required.

In order to separate the residual oil from the aqueous solution, the 100 mL content of each bottle was shaken for about five minutes with 50 or 75 mL of cyclohexane. The aqueous phase was discarded. In case that no satisfactory separation was achieved due to the formation of a stable emulsion, sulfuric acid, magnesium sulfate or sodium chloride were added to facilitate the liquid-liquid phase separation.

About 10 mL of the cyclohexane extract was removed from the flasks with a syringe and transfered into GC vials of 2 mL volume. A 0.45 μm PTFE filter was fitted to the syringe before filling the vials. It was later discovered that the extracts needed to be more concentrated since the oil content in many samples was close to the detection limit of GC analysis. Reproducibility of the biodegradation trials was tested by repeating the experiments with 3 days of incubation for all oils. The GC profiles obtained are very similar (Sacha oil, Fig. 1).

Biodegradation in soils. The microbial degradation of oil was investigated in lab trials (in the climate-controlled closet) on artificially contaminated soil material. Three different fresh crude oils (Sacha, Shushufindi and Shuara) were added in a single application to four containers holding 10 kg soil (compacted to its original density) each at a rate of 3 L of crude per m^2. One of the containers remained untreated (I), the second was fertilized with a commercial N-P-K fertilizer (II), and the third was supplemented with a starter culture (bacterial broth). The fourth was the control, in which microorganisms were killed with 2% sodium azide solution.

Residual oil remaining in the upper 5 cm of the soil was determined on a composite sample taken from each container weekly. The soils were occasionally moisturized using a water sprayer.

2.3. Analytical Methods

General. As oil can very easily become biochemically oxidized, it is necessary to extract it from the water, in which it is present in dissolved and emulsified form, immediately after sampling. A number of solvents can be used, such as cyclohexane, toluene, carbon tetrachloride or trichlorotrifluoroethane. The latter is rarely employed today because of environmental considerations and the worldwide ban of CFCs.

Gravimetric methods of oil determination are the most simple, but are not very sensitive and can give erroneous results due to the loss of volatile components.

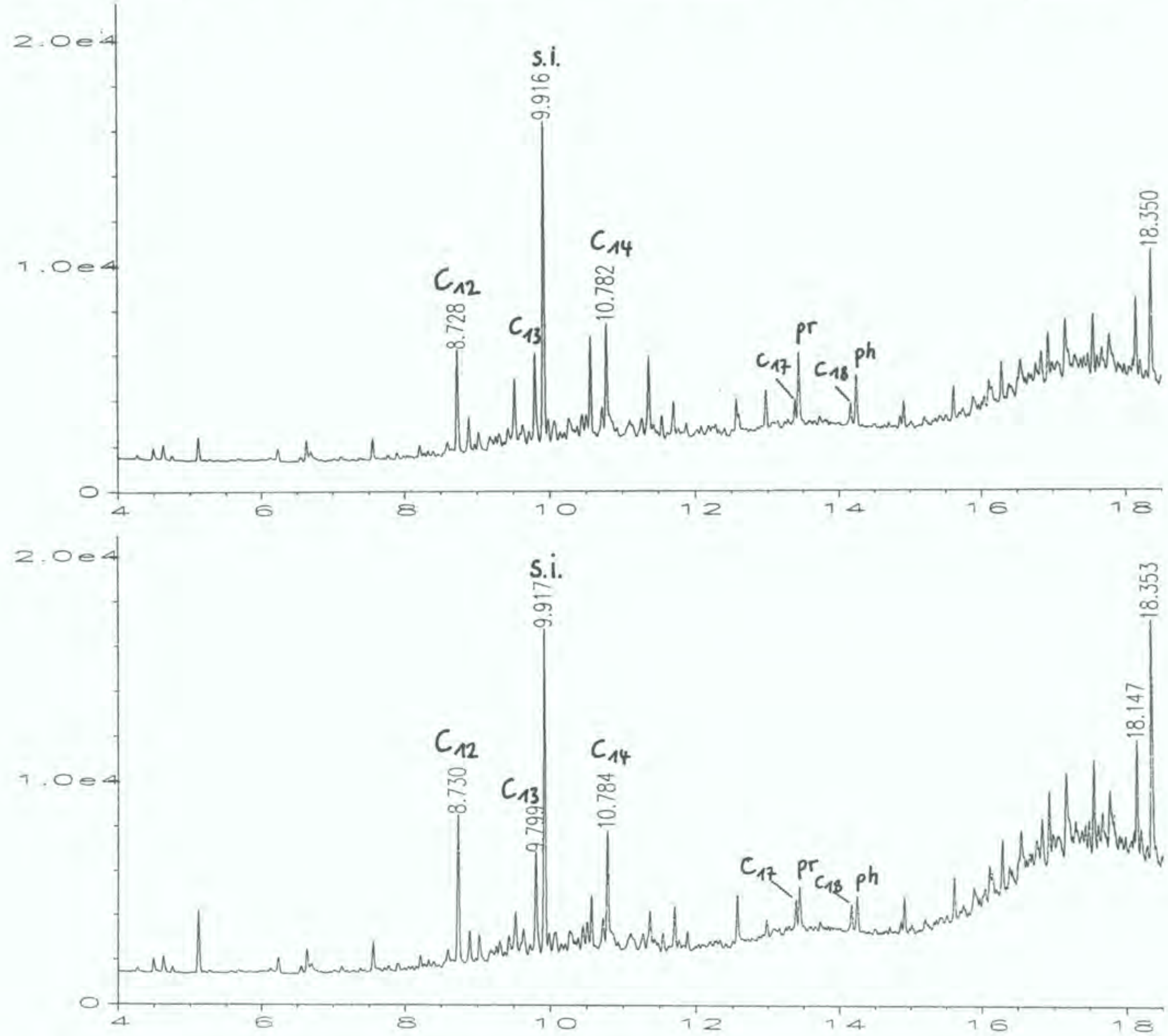

Fig. 1. Gas chromatograms of two separate biodegradation trials with Sacha oil for 3 days of incubation under (identical) optimal conditions. The composition of the residues is very similar. x-axis = retention time on the GC column in minutes; y-axis = peak magnitude; C_{12}, C_{13}, C_{14} = n-alkanes with number of carbon atoms; s.i. = solvent impurity; pr = pristane; ph = phytane.

Fig. 1. Cromatogramas para dos ensayos distintos de biodegradación con crudo del campo Sacha para 3 días de incubación bajo las mismas condiciones óptimas. La composición de los residuos es muy parecido. eje de abscisas = tiempo de retención en la columna de cromatografía de gases (CG) en minutos; eje de ordenadas = magnitud del pico; C_{12}, C_{13}, C_{14} = n-alkanos con número de átomos de carbón; s.i. = impureza del solvente; pr = pristano; ph = fitano.

Different ultraviolet (UV), infrared (IR) spectrophotometric and luminescent methods are the most popular. Analysis based on column and thin-layer chromatographic separation allows the possibility of the separate determination of e.g. volatile and non-volatile polyaromatic hydrocarbons, resins and asphaltenes.

Glass capillary gas chromatography (GC) method. Crude oil samples and extracts from the trial series were dissolved in cyclohexane, filtered through PTFE membrane filters of 0.45 μm and subsequently analyzed by gas chromatography with no further pretreatment or separation. The chromatograms obtained after injection of the samples display a great number of peaks which correspond to a large number of individual chemical compounds.
Hydrocarbon compounds have been identified on the basis of retention time comparisons with authentic standards and with literature values.

It should be stressed that 100% positive identification of a given peak (which may contain more than one compound) requires additional analyses with a mass spectrometer in series with GC. GC-MS analysis was not performed in the present study since we decided to adapt our analytical methods to the facilities available in Ecuador. Through careful evaluation of the GC results obtained, the use of reference compounds and extensive literature studies, however, the peak identification has a very high level of accuracy.

The glass capillary GC method which was used resolves the n-alkanes and the isoprenoids (pristane and phytane) but leaves a large number of unresolved saturates (i.e. the cycloalkanes). Only a small fraction of the mono- and diaromatics was resolved and a number of unresolved compounds was left. Because the saturate, aromatic and asphaltic fractions were not separated for reasons of simplicity, some peaks in the GC profile are superimposed by others, e.g. 2-methyl-

Compound	Formula	Molecular weight	Specific gravity	Melting point	Boiling point
		g/mole	g/cm^3	°C	°C
Isopropylbenzene	$C_6H_5CH(CH_3)_2$	120.2	0.864	-96	153
Propylbenzene	C_9H_{12}	120.2	0.864	-99	159
Naphthalene	$C_{10}H_8$	128.2	0.997	81	218
n-Dodecane	$CH_3(CH_2)_{10}CH_3$	170.3	0.749	-9.6	216
2-Methylnaphthalene	$C_{10}H_7CH_3$	142.2	1.000	34-36	241-242
1-Methylnaphthalene	$C_{10}H_7CH_3$	142.2	1.001	-22	240-243
n-Pentadecane	$CH_3(CH_2)_{13}CH_3$	212.4	0.769	9.9	270
n-Hexadecane	$CH_3(CH_2)_{14}CH_3$	226.4	0.773	18	287
Pristane	$C_{19}H_{40}$	268.5	0.785	nd	296
n-Octadecane	$CH_3(CH_2)_{16}CH_3$	254.5	0.777	29-30	317
Pyrene	$C_{16}H_{10}$	202.3	nd	150	404

Table 1. Reference compounds used in the calibration of the GC instrument. The hydrocarbons are listed in the order as they appear in the gas chromatogram.
Tabla 1. Compuestos de referencia usados en la calibración del cromatógrafo de gases. Los hidrocarburos son listados en el orden de elución en el cromatógrafo.

naphthalene coincides with n-tridecane (C_{13}-alkane). The GC method was designed and applied mainly to screen different microbial cultures for their capability to degrade crude oil hydrocarbons. Changes in the "finger prints" of the oil fractions from biodegradation trials with inoculated cultures were readily detectable and reproducible when compared with sterile controls. The comparison with controls made it possible to discount losses by evaporation.

A mixed standard of eleven typical constituents of crude oils was prepared which was used to calibrate the GC instrument. The reference compounds employed fall into the following groups:

- Straight chain aliphatic hydrocarbons (number of carbon atoms): n-dodecane (12), n-pentadecane (15), n-hexadecane (16), n-octadecane (18)

- Isoprenoids or branched alkanes: pristane

- Monocyclic aromatics: isopropylbenzene, propylbenzene

- Polycyclic aromatics (number of condensed rings): naphthalene (2), 1-methylnaphthalene (2), 2-methylnaphthalene (2), pyrene (4)

Analysis of waters. Alkalinity was determined by titration with 0.02 m HCl to pH 4.5 (APHA Standard Method No. 403). The water samples for cation analysis were filtered through 0.45 μm cellulose nitrate membrane filters (Sartorius, Germany) and were immediately acidified with 3-4 mL of concentrated nitric acid (Merck Suprapur) per litre of sample. Filters were retained for gravimetric determination of suspended solids. Water samples were analyzed at a commercial laboratory (XRAL, Canada). Analysis for dissolved metals was by multi-element ICP-AES. Trace metals like copper, lead, zinc, cadmium, selenium and vanadium, which were present in some samples in concentrations close to the detection limit of ICP-AES, were additionally determined by ICP-MS. Major anions were determined on unacidified samples by ion chromatography at XRAL.

Calculation of mole equivalents. The calculation of mole equivalents or milliequivalents is a useful tool to check the quality of analytical results, and is needed for the construction of Schoeller Diagrams for formation waters (see section 5.2.). The sum of the mole equivalents of major cations (Ca^{2+}, Mg^{2+}, Sr^{2+}, Na^+, K^+) should be identical with the sum of major anions (Cl^-, Br^-, SO_4^{2-}, HCO_3^-) in a sample. Each analytical value (in mg/L) is multiplied by a factor which is: valence of the element divided by its atomic weight (in g/mole). In the case of dissolved calcium (Ca^{2+}), the factor is: **2/40** (valence/molar weight in g/mole) = **0.05**.

3. The Environment of the Ecuadorion Amazon Region

The subandean Ecuadorian Amazon lowland, also known as Oriente, forms part of the upper Amazon basin. Its major (northern) part is drained by the Río Napo which joins the Amazon River downstream of Iquitos in Peru (Fig. 2). The Oriente slopes down from the Andes, encompassing over 13 million hectares of tropical rain forest which represents 46% of Ecuador's total area. It is limited to the west by the Cordillera de los Andes and to the north by the Río San Miguel and the Río Putumayo, which constitute the political border to Colombia. To the east and south, the Oriente is limited by the border with Peru. The five provinces of Ecuador which make up the Oriente, from north to south, are: Sucumbios, Napo, Pastaza, Morona Santiago and Zamora Chinchipe.

3.1. Geology of the Oriente Basin

The Oriente forms part of the upper Amazon basin, a large sedimentary structure which extends from the Andes to the Precambrian shields of Guayana and Brazil. Up to the Miocene, the shields to the north and south were the source rocks for the clastic sediments in the basin, and later the northern Andes. From the Cretaceous to the Tertiary, 3000 to 4000 m of terrigenous, marine and continental sediments, intercalated with volcanic clastics (ashes), have been deposited (Canfield et al. 1982).

The Oriente basin is subdivided into three smaller basins: the Napo basin which stretches from northern Ecuador to southern Colombia, the Pastaza basin in the south of Ecuador and northern Peru, and the Ucayali basin in Peru. The axis of the Napo sub-basin runs close to the Lago Agrio and Sacha oil fields (Fig. 3).

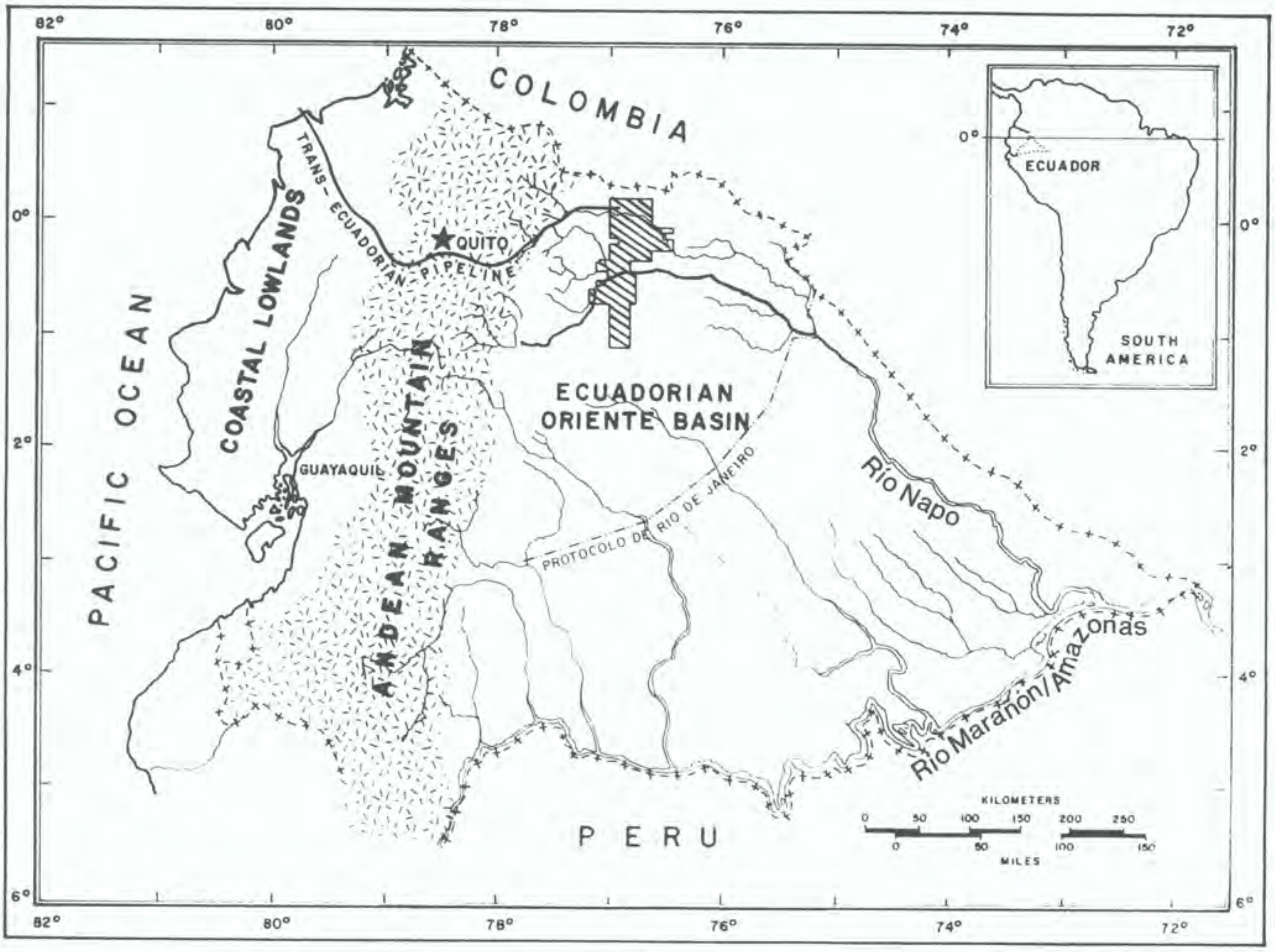

Fig. 2. Map of Ecuador showing the three major geographic units. The hatched area in the Oriente marks the concessions and oil fields of *Petroecuador* from which most samples were taken (modified from Canfield et al. 1982).

Fig. 2. Mapa del Ecuador mostrando las tres regiones geográficas mayores. El área marcada en el Oriente indica las concesiones y campos petroleros de *Petroecuador* en donde fueron tomadas la mayoria de las muestras (modificado de Canfield et al. 1982).

The crystalline Precambrian basement is overlain by terrigenous Jurassic sediments. Over a discordant contact follows the **Hollin Formation** of the Lower Cretaceous (Aptium/Albium, Fig. 4). It crops out along exposed river banks of the upper Río Napo and its tributaries and around Tena at the western margin of the basin. The mostly continental Hollin Formation consists of white, coarse and porous sandstones with intercalated dark siltstones and shales in the upper part. Its thickness varies between 80 m in the north and 200 m in the southern part of the basin. The Hollin Formation is the principal hydrocarbon reservoir in the fields of the Oriente.

The **Napo Formation** of Cenomanian to Campanian age can be found in outcrops close to Puerto Napo, also on the upper Río Napo. The Formation begins with volcanics and dark gray marine shales, followed by glauconitic sandstones which indicate very slow sedimentation. The sandstones are interbedded with dark shales. Banks of micritic limestones occur in the middle and upper Napo Formation. The sandstones "T" and lower "U", which have been deposited in a deltaic environment, contain significant accumulations of oil. The Napo Formation is between 400 m and 800 m in thickness and decreases to the East.

Over an eroded discordant contact follow the shallow marine to terrestrial deposits of the **Tena Formation** (Eocene). It is made up of red beds and some coarser sediments. The basal conglomerates, sandstones and red beds of the **Tiyuyacu Formation** lie conformably over the Tena red beds. The clastic continental deposits are characterized by abrupt vertical and lateral facies changes. They have a thickness of about 500 m in the Coca area. In the sequence follow the gray shales and sandstones of the **Orteguaza Formation** of probable Oligocene age.

The Miocene and Pliocene is represented by the red beds with intercalated sandstones (alluvial fan deposits) of the **Chalcana, Arajuno, Chambira and Mesa Formations**. The coarse sediments of the fluvial fans of the **Mesa Formation** of Pliocene to Pleistocene age cover the Tertiary deposits and decrease in grain size and thickness to the east of the basin. They form isolated terraces (mesas) which are separated by faults. The Mesa Formation is a volcanic-fluvial piedmont deposit, whose lithology consists of fine- to medium-grain, greenish-grey sandstones intercalated with coarse conglomerates.

The Quaternary deposits consist of alluvions of major rivers. The dominant soils which have developed in the area are tropical entisoils.

Geology of the petroleum deposits. In the plains in front of the subandean mountains in the Oriente rich oil-fields are located in the Río Napo basin and along the Río Aguarico.

The productive fields of oil and gas in the Oriente belong to a long belt which strikes parallel to the belt of the Andes (Fig. 3). Similar to Ecuador, the fields in Colombia (Mocoa oilfields) and Peru (at the Río Pastaza and in the Ucayali basin) are situated in the uttermost western margin of the upper Amazon basin.

The productive horizons in Ecuador belong to the Lower and Upper Cretaceous and Eocene, in Colombia and Peru to the Lower Cretaceous. Mother rocks are marly shales of the Lower (Hollin Formation) and the Upper Cretaceous (Napo Formation). Migration of oil probably took place in the Oligocene (Canfield et al. 1982).

About 80% of oil production in the Sacha field, the second biggest in the Oriente, comes from a marine

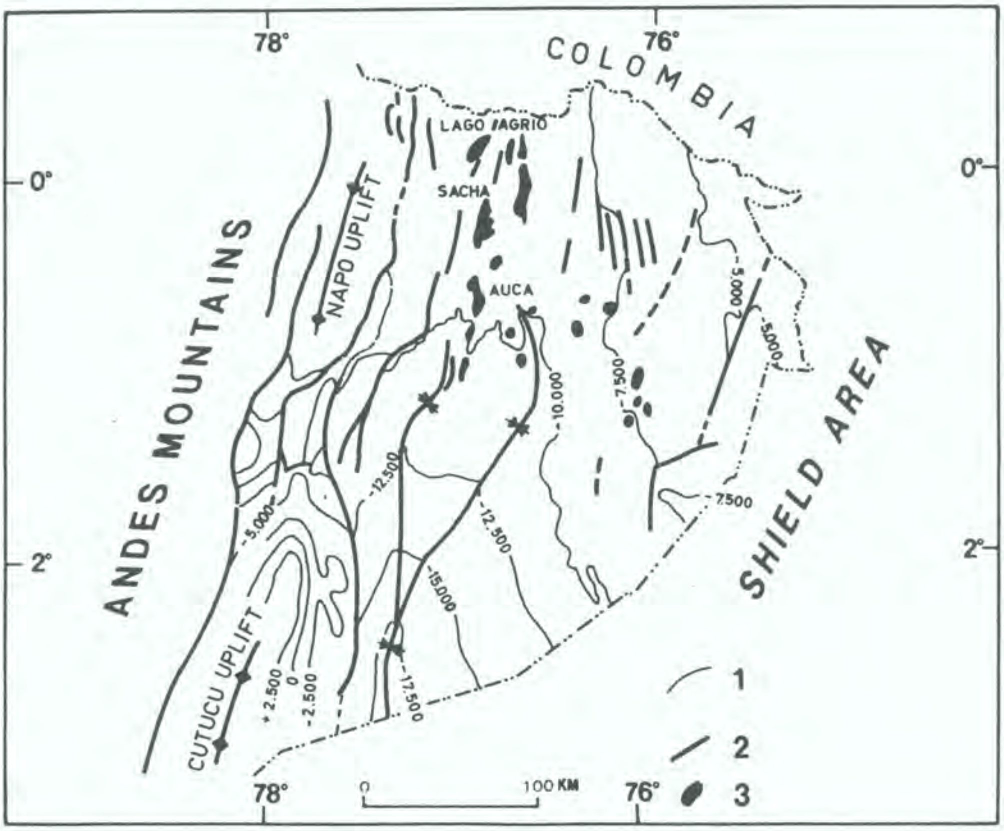

Fig. 3. Oriente basin and major oil fields (modified from Canfield et al. 1982). 1 = depth contours of Cretaceous in feet, 2 = major faults, 3 = oil fields

Fig. 3. La Cuenca Oriental y los mayores campos de petróleo (modificado de Canfield et al. 1982). 1 = contornos profundos del Cretáceo en pies, 2 = fallas mayores, 3 = campos de petróleo.

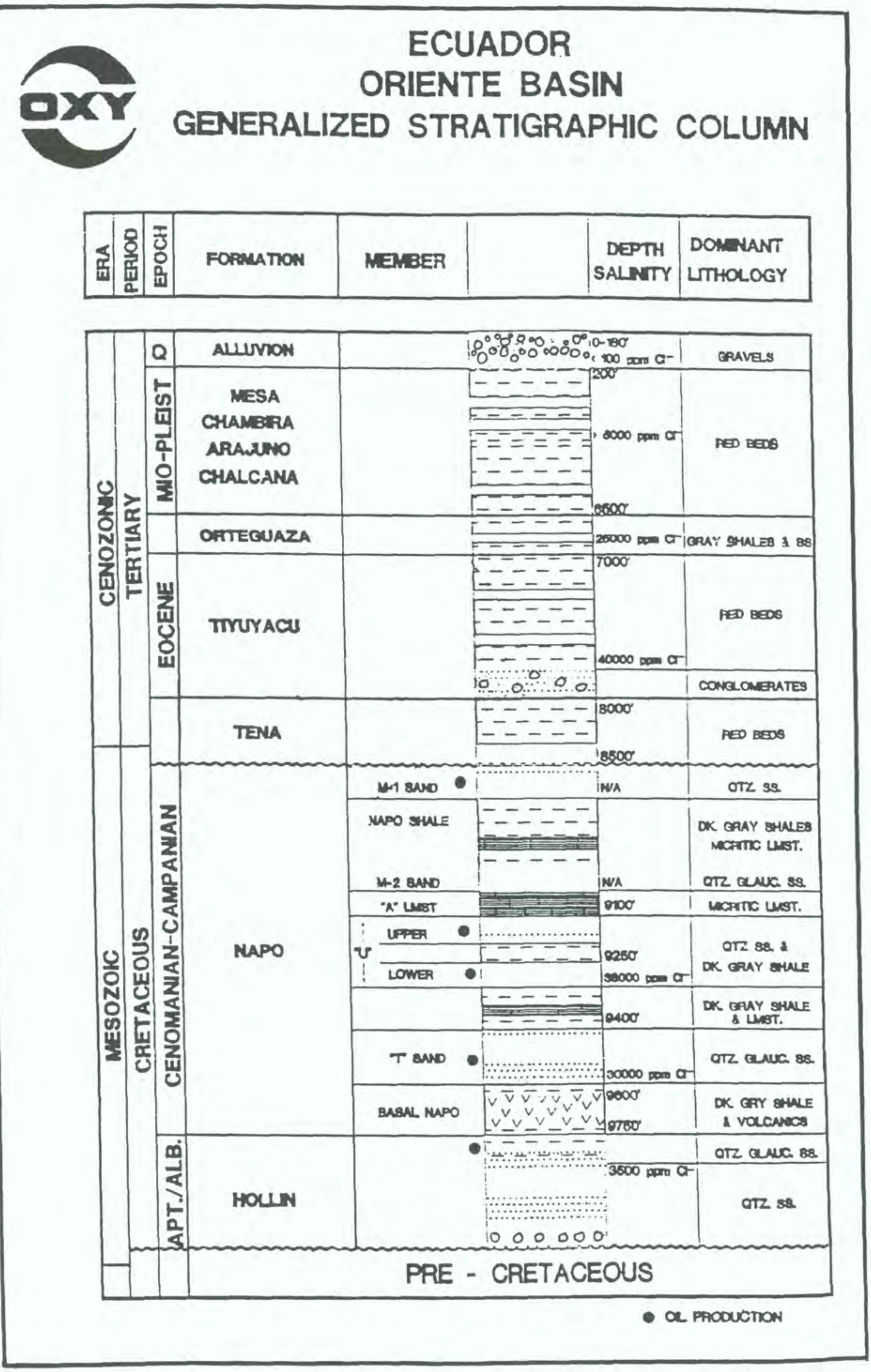

Fig. 4. Generalized stratigraphic column of the Oriente basin.
Fig. 4. Columna estratigráfica general de la Cuenca Oriental.

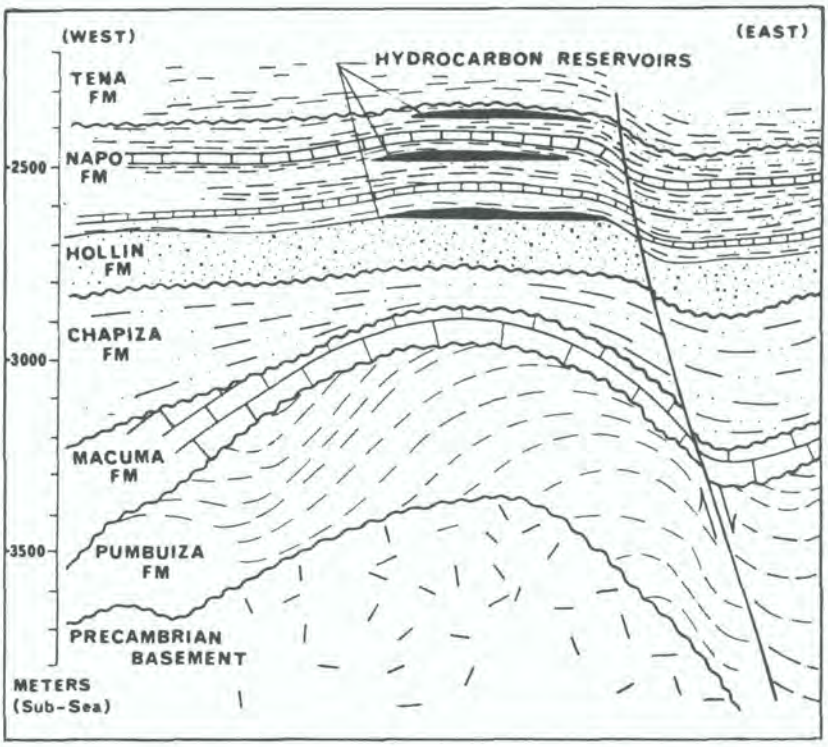

Fig. 5. Cross section of typical hydrocarbon trap in Oriente basin (from Rigo de Righi & Bloomer 1975).
Fig. 5. Corte transversal de una trampa típica petrolífera en la Cuenca Oriental (tomado de Rigo de Righi & Bloomer 1975).

sandstone of the Hollin Formation of the Lower Cretaceous, which is sealed off by an impermeable shale horizon (Fig. 5). Oil from the Hollin main sands have about 29° API. In the Napo Formation, the main reservoirs are termed "T", "U" and "M1" which are sandstones of good porosity and permeability. The "T" and "U" sandstones host oil of 26-32 °API.
Heavy asphaltic and sulfur-rich crude oils are found in the southern and southeastern part of the Oriente.

3.2. Climate and Hydrology

The climate in the area is wet tropical with pronounced seasonality, with one relatively dry period in the year, from December to March (Fig. 6). Due to the lack of meteorological and hydrological stations in the Río Napo catchment, limited data on rainfall and streamflow are available.

The Andean Cordillera acts as an orographic barrier where humid air from the Amazon lowland condenses and precipitates. Rainfall is highest in the foothills of the Andes and decreases in easterly direction. At the Puyo station in the Andean piedmont, annual rainfall is 4412 mm and at Limoncocha station on the Río Napo, the value is 3244 mm (Gómez 1994). Further to the east, close to the Peruvian border, annual precipitation is around 2300 mm.

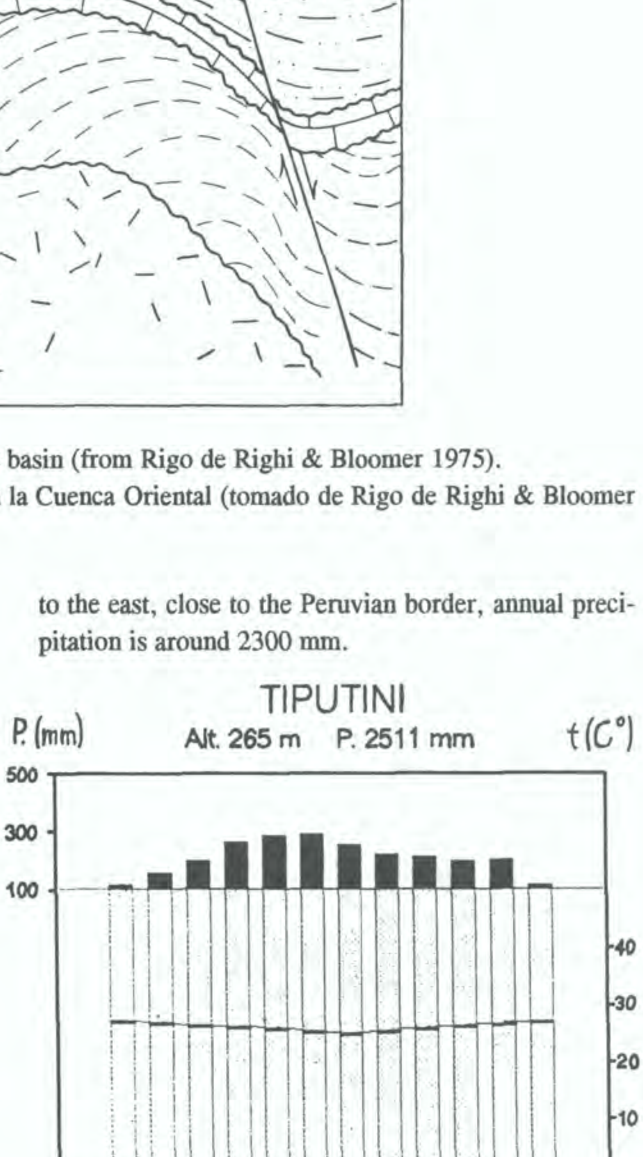

Fig. 6. Mean monthly rainfall and temperatures at the Tiputini meteorological station from 1985-1994, Yasuni National Park, Oriente.
Fig. 6. Promedio mensual de precipitaciones y temperaturas en la estación metereológica Tiputini desde 1985 a 1984, Parque Nacional Yasuni, Oriente.

Temperatures in the Oriente vary between an average minimum of 20 °C at night and a mean daily maximum of 32 °C. The day and night average is 26 °C with minimal monthly variations, the lowest temperatures being registered in June to August.

The major, northern part of the Oriente is drained by the Río Napo, a tributary to the Amazon. Its most important tributaries in the region are the Río Aguarico and Río Coca. The minor, southern part of the Oriente is drained by the Conambo, Bobonaza, Pastaza and Morona Rivers which join the Marañon (Amazonas) upstream of the Río Napo.
The flow of the Río Napo is characterized by quick responses to rainfall in its catchment, highly variable flow and short-time events of very high flow. This it attributed to the occurence of very fine-grained sediments along the river course which have low permeability and hence limit infiltration and retention capacity of the river system. Due to its Andean catchment with high erosion rates, the water of the Napo is rich in suspended load during most of the year.

3.3. Geomorphology and Vegetation

The western part of the Oriente comprises the subandean mountains whith elevations of about 900 m above mean sea level (MSL), and the eastern plain which is situated about 200 m above MSL. The latter is characterized by a moderately undulating relief and dissected piedmont alluvial plains of Tertiary age which are crossed by extensive areas of Pleistocene alluvial sediments, mainly sands and silts, along major rivers like the Río Napo and its tributaries.
The major rivers like the Napo and the Aguarico have very narrow floodplains and display a low sinuosity. The rivers have cut into their older terraces. Lateral migration rates in the Napo are very low and are restricted by the lithology of older alluvial deposits.

As a result of late Andean tectonic activity, large blocks of the upper Amazon plain have been lifted while others have subsided. The lagoons and lakes close to the course of the Río Napo (e.g. Limoncocha) are considered as "tectonic lakes" (Fig. 7). The course of the Río Napo itself seems to follow tectonic faults (*lineamemtos*) in some sections.

The Oriente forests form part of the American or neotropical humid tropical forest Formation. Constantly high humidity, high temperatures and rainfall around 3000 mm per year offer ideal conditions for the growth of a highly diverse humid tropical forest. The tropical rainforest ecosystem is considered to be fairly homogenous in the Ecuadorian Oriente. The rainforest is divided into three different ecological units: forest of the dissected plateaus and hills (*bosque de tierra firme*), with a canopy height of 15 to 30 m; forest temporally inundated (*bosque estacionalmente inundado*) located on alluvial soils along streams and rivers; and swamp forest (*bosque permanentemente*

Fig. 7. Limoncocha lake, close to the Río Napo, a Biological Reserve.
Fig. 7. Laguna Limoncocha, cerca del Río Napo, que forma parte de la Reserva Biológica Limoncocha.

inundado) situated in swampy depressions with perennially standing water.
It is estimated that the lowland forests of the Oriente are home to between 9,000 and 12,000 species of vascular plants (ferns and seed plants), many of them endemic to the area.

3.4. Wildlife

The tropical forests of the upper catchment of the Amazon are among the most biologically diverse natural ecosystems on earth. Some figures on the biodiversity of the flora and fauna of the region are available for the Yasuni National Park which occupies an area of 982,000 ha. The park was created in 1979, modified several times, and declared a Biosphere Reserve in 1989 by UNESCO.

In the Yasuni park, a large number of rare species or species in the danger of extinction are found, like Amazon manatees, freshwater dolphins, giant otter, four different species of caymans, jaguar, ocelot, giant armadillo, tapir, spider and woolly monkeys, harpy eagle, toucans, and others. About 270 reptile and amphibian species, nearly 500 different birds (including 18 species of parrots, macaws and parakeets), more than 250 fish species and about 300 mammals have been detected in the Yasuni park (oral comm., *Ecuambiente*). On a single tree, enthymologists have found more insect species than exist on the entire North American continent (a total of about 100,000 species has been registered so far).

3.5. Population

The large majority of the population in the Oriente today are non-indigenous settlers who migrated from other parts of the country (the Andes highlands and the coast). A census in 1982 showed that the regional population in the Oriente of 318,000 had grown by 4.9% annually, nearly twice the national rate. In oil-producing areas, where settlers used newly built roads to penetrate the rain forest, the population grew by 8% each year (Kimerling 1991). Population density in the Oriente today is about 3 inhabitants per km^2 as compared to 74 in the sierra (Andes) and 78 on the coast (INEC 1991).

The region is home to eight groups of indigenous people, estimated to comprise from 85,000 to 100,000 people. The Quichua and Shuara who historically descended from the upper Napo basin, from the area around Tena, account for the great majority. The other groups (available population estimates in brackets) are: Achuar, Cofane (300), Shiwiar (600), Siona and Secoya (together about 350), and the Waorani, which are presented in some detail below.

The region between the Tiputini and Curaray rivers is the homeland of the Waorani tribe which today consists of about 1,300 people living in an ethnic reserve of 772,000 hectares. Since the Waorani represent the indigenous group with the lowest degree of aculturization in the Oriente, which in parts still continue their traditional lifestyle, they merit a more detailed description.
The Waorani population has repeatedly suffered from clashes with non-indigenous invaders, e.g. from rubber tapping activities at the beginning of this century. Missionaries (the first catholic padres arrived around 1620) also had a heavy impact on the integrity and cultural identity of the Waoranis who have a fame of being brave warriors. As late as 1986, the Tagaeri, a nomadic tribe belonging to the Waoranis, killed two missionaries.

The Waoranis live in a semi-nomadic way and collect fruits from the forest, cultivate yuca, bananas, chontadura and maize in semi-permanent gardens. Plants are used to prepare food, juices, dyes, medicine, poisons, and for ritual purposes.

The Waoranis hunt a large number of animals for food and decorative purposes, mainly wild pigs, pecaries, monkeys, turkeys and other birds. To a minor extent, fishing provides another animal protein source. Tigers are only hunted for their teeth. The traditional tools for game hunting are blowpipes and spears, which are now being replaced by fireweapons. Waorani food habits are closely related to available species in the rainforest. Waoranis reject to eat meat of domestic pork or beef and prefer, e.g. monkey meat instead.

The first social impact related to petroleum extraction occurred in the 1940s when Shell undertook seismic exploration in the area and employed Waoranis for field work. Part of the indigenous population was relocated with the help of a baptist mission. Probably from the same time dates the arrival of fireweapons in what is now the Waorani ethnic reserve.

4. Properties of Crude Oil and Formation Waters

4.1. Composition and Chemistry of Oil and Gas

At present, more than 800 individual compounds have been identified in mineral oils. Among them are low- and high-molecular weight aliphatic, naphthenic and aromatic hydrocarbons, high-molecular unsaturated heterocyclic compounds (resins and asphaltenes) as well as numerous oxygen, nitrogen and sulphur compounds. Metals like nickel, vanadium, copper and iron may also be found in crude oils.

Natural gas is a mixture of C_1-C_5 hydrocarbons dominated by methane (60-80%) in which also carbon dioxide, helium, hydrogen sulfide, nitrogen, and other gaseous compounds occur. The gas may be dissolved in the liquid phase of an oil reservoir or form a cap above the oil layer.

Crude oil is a mixture of several classes of hydrocarbons:

n-alkanes and iso-alkanes, paraffinic fraction: saturated hydrocarbons with the general formula C_nH_{2n+2} of which n_C = 1-4 are gases (methane, ethane, propane, butane), n_C = 5-16 are liquid (n-pentane etc.) and $n_C > 16$ are solid. They make up between 10 and 70% of crude. Iso-alkanes are also known as branched alkanes or isoprenoids, e.g. pristane, phytane.

Cycloparaffines or naphthenes (C_nH_{2n}): they make up 25-75% of crude oils. They consist of mono- and polycyclic saturated alkanes, e.g. cyclopentane and cyclohexane. Polycyclic, condensed naphthenes of high molecular weight also are characterized by high boiling points and fall into the asphaltenic group (asphaltic oils).

Aromatic fraction (C_nH_{2n-6}): monocyclic (e.g. benzene, toluene, xylene) and polycyclic aromatic hydrocarbons (naphtalene, anthracene, phenanthrene) form usually less than 20% of the crude. Aromatic compounds are frequently enriched in the heavy fraction and the distillation residue.
Naphthalene and its methylated isomers (methyl-, dimethyl- and trimethylnaphthalenes) frequently form the major aromatic compounds in diesel fuel (Bundt et al. 1991).

Unsaturated heterocyclic compounds: resins, asphaltenes, asphaltenic acids and their anhydrides make up a minor fraction of crude.
The content of the elements sulfur and nitrogen which form hetero compounds (polar fraction), along with nickel and vanadium, is highest in the heavy oil fractions like asphaltenes. Sour crudes contain H_2S in higher concentrations. Nickel and vanadium typically appear in porphyrines, geochemical tracers that demonstrate the biological origin of crude oil, which are products of the decomposition of hemoglobine and chlorophyll. Although iron (in haemin) and magnesium (in chlorophyll) are the metals originally bonded to these compounds, during diagenesis ion exchange takes place, and nickel and vanadium are substituted (Miles 1994).

Technically, crude oil is characterized by its specific gravity (between 0,7-1.06 g/cm^3 at 20 °C) and its behaviour upon fractionated distillation. Crude oils are also classified according to degrees API gravity (American Petroleum Institute) measured at 60 °F (equivalent to 15,5 °C).

gravity API = (141.5 ÷ specific gravity at 60 °F) - 131,5

Conversion table:

°API	**specific gravity at 60 °F**
10	1.000
15	0.966
20	0.934
25	0.904
30	0.876
35	0.846
40	0.825
45	0.802
50	0.780

Most crude oils have API gravity values between 27° and 35°. Oils are grouped into heavy crude (<20 °API), medium (20-35°) and light crude (35-45 °API).

Crude oils can also be distinguished by the products which they render at different temperatures in the distillation process:

petrol ether	40-90°C
gasoline or nafta (mainly n- and iso-alkanes and cycloalkanes)	90-200 °C
kerosene/petroleum (aromatics 10-40%, naphteno-aromatics, condensed cycloparaffines)	200-260 °C
diesel/gas oil (compounds with 15-25 carbon atoms, n-alkanes)	260-330 °C
fuel oil, lubricant oils (compounds with 26-40 carbon atoms, n-alkanes, cycloparaffines, condensed aromatics of high molecular weight like phenanthrene; heterocyclic compounds, asphaltenes and resins at higher boiling points)	>330 °C

The composition of crudes often is related to its stratigraphic level in an oil field. In the lower levels, paraffinic oils of low density and sulfur content dominate, whereas in the higher horizons, aromatic oils of higher density and sulfur (>1%) are found. Heavy crude oils are characterized by being low in alkanes, high in asphaltenes and sulfur. They may form due to: microbial degradation, evaporation of volatiles, location at the rims of an oil deposit or location in higher stratigraphic positions.

Viscosity is an important parameter which controls the recovery of oil from the producing formation. It depends on temperature, pressure and chemical composition of the crude oil.

4.2. Microbial Degradation of Crude Oil

The microbial decomposition of toxic organic compounds has been demonstrated for a whole range of substances, including petroleum hydrocarbons, chlorinated solvents and pesticides.

The degradation of crude oil by bacteria and fungi can be understood as a biologically mediated oxidation. Hydrocarbon-degrading micro-organisms which use oil as their energy source are ubiquitous and may be found in any soil. The most biologically favourable environments for bacteria and fungi generally occur in warm, humid conditions. Under ideal conditions, with no kinetic barriers, all organic material would eventually be converted to the simplest inorganic compounds, carbon dioxide and water. In practice, complete breakdown is never reached, and intermediate products of equal or even greater toxicity and persistence may be produced.

Another important reason for incomplete microbial utilization of oils is substrate limitation. It is known that a close relationship exists between substrate concentration and the rate at which a substrate is biodegraded. In practice, this means that the degradation rate decreases with diminishing concentrations of the petroleum compound which serves as a energy source to the microorganisms.

Most microorganisms require oxygen for respiration (aerobic respiration) and the breakdown of organic matter, but when oxygen concentrations are depleted some bacteria can use alternatives, such as sulfate, nitrate or carbon dioxide (anaerobic respiration). Organisms which can live either with or without oxygen are called facultative anaerobes. In contrast, obligate anaerobes are organisms which do not tolerate the presence of oxygen. Therefore, the absence or presence of oxygen, and the supply of nutrients are the most important factors affecting microbial activity.

Microbial degradation of crude oil by anaerobic bacteria is extremely slow and hence negligeable. If there was significant microbial decomposition in the absence of oxygen, most deposits of petroleum would not exist for any prolonged period of time.

Generally, the bacterial decomposition of petroleum components is selective and affects primarily hydrocarbons of lower molecular weight which also are easily lost by evaporation.

The order of relative ease of attack of microorganisms on particular groups of saturated hydrocarbons can be given as n-alkanes > alkylcyclohexanes > acyclic isoprenoid alkanes > C_{14}-C_{16} bicyclic alkanes > steranes > hopanes (Alexander et al. 1983).

The aromatic degradation by microorganisms progresses from lower molecular weight, less complex molecules to larger, more complex molecules. The order of susceptibility to biodegradation is broadly monoaromatic > diaromatic > triaromatic (Connan 1984).

There are different ways in which microorganisms attack hydrocarbons. Following a first oxidation step mediated by enzymes (*oxygenase*), aliphatic hydrocarbon chains are broken up. In the evolving bacterial degradation process both the number and aggresivity of bacteria increase which are able to metamobilize even the long-chained paraffines. Among these microorganisms are pseudomonad bacteria like *Mycobacteria*, *Nocardia* and *Corynebacteria* as well as *Candida* yeasts (Schlegel 1992). Many pseudomonads are able to completely oxidize paraffinic hydrocarbons, while others produce intermediate compounds like alcohols, fatty acids and their esters.

Aromatic hydrocarbons are decomposed mainly in two steps: The aromatic ring (e.g. of benzene, toluene, anthracene) is oxdized through the *dioxygenase* enzym system to brenzcatechin (catechol, 1,2 dihydroxybenzene) (Fig. 8). In a second step, the aromatic ring is cracked by oxidation, mediated by *dioxygenase*, yielding intermediate products like carboxylic acids and aldehydes. Two important pathways are known for the degradation of alkylaromatic hydrocarbons by aerobic bacteria: one involves the oxidative attack on the aromatic ring whilst the other involves oxidation of the alkyl substituent (e.g. methyl groups of dimethylnaphthalene). Oxidation of aromatic ring carbon is an energy-providing process which often results in complete degradation of the substrate. Attack on the alkyl substituents does not always provide energy but can occur as a cooxidation process when another compound is utilized as energy source.

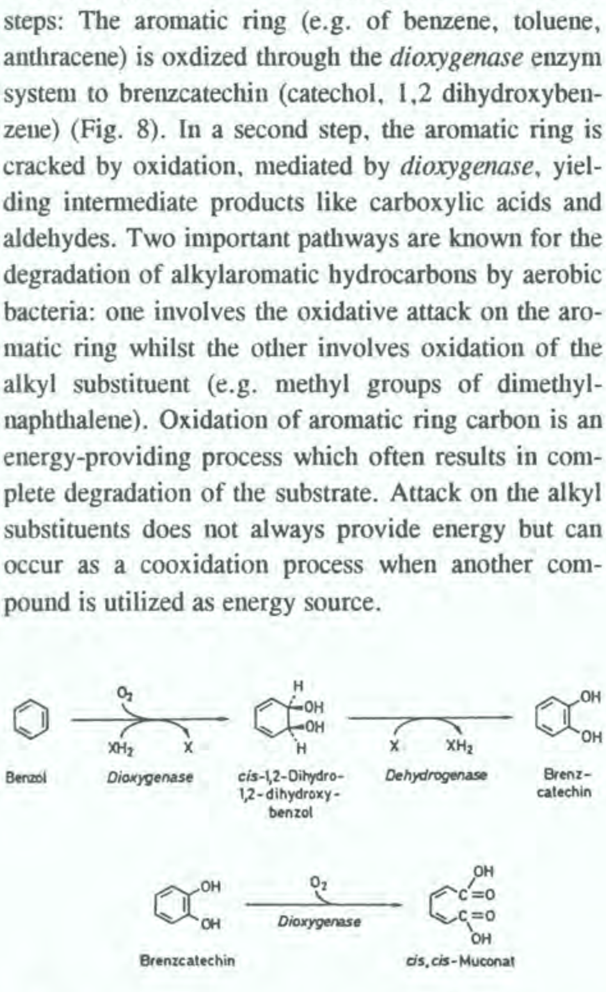

Fig. 8. Microbial degradation and oxydation of benzene representing a typical aromatic compound: multiple enzym attack on the ring structure results in cracking and the formation of a dicarboxylic acid (from Schlegel 1992).

Fig. 8. Degradación y oxidación microbiológica de benceno representando un compuesto aromático típico: ataque múltiple enzimático sobre la molécula resultando en la ruptura del anillo y formación de un ácido dicarboxílico (tomado de Schlegel 1992).

Oxidation of the unsubstituted ring in aromatic hydrocarbons is the preferential degradation process (Rowland et al. 1986) and may occur before significant bacterial degradation of n-alkanes takes place. Phenanthrene (three condensed aromatic rings), and its methylated isomers in particular, generally are more resistant to microbial oxidation than naphthalene (two aromatic rings) and methylnaphthalenes. The stereochemistry or the position of alkyl substituents on aromatic rings influences degradation. Solanas et al. (1984) found that the persistence of alkylnaphthalenes increased as the number and size of alkyl substituents increased, i.e. C_0 degrades $> C_1 > C_2 > C_3 > C_n$ (where n = carbon number of alkyl substituents on an aromatic nucleus). They also observed differences in the susceptibility of individual methyl- and dimethylnaphthalenes depending on the position of the methyl groups (steric effects).

It has been demonstrated that long-chained alkanes, polyaromatics and asphaltenes form the residue in highly weathered oils which resists biological degradation for a long time. In highly biodegraded crude oils, the paraffinic fraction may be missing.

Most microorganisms like bacteria and fungi grow on solid surfaces and coat the grains of the soil or aquifer. They attach themselves with extra-cellular polysaccharides, forming a stable protective biofilm. An estimated 95% of the bacterial population may be attached in this way, rather than floating in the aqueous medium itself. The population density of micro-organisms depends on the supply of nutrients and removal of harmful metabolic products.
Microbe populations are largest in the nutrient-rich humic upper parts of the soil, and decline with decreasing nutrient supply and oxygen availability at greater depths. Many sub-surface microbes, however, prefer lower nutrient conditions.

4.3. Transport and Dispersal Mechanisms of Petroleum

Distribution of oil in waters. Oil is distributed in waters in different forms: dissolved, surface films, emulsion and sorbed fractions. Interactions between them and ecological effects of these fractions are complicated and diverse, and depend on the specific gravities, boiling points, surface tensions, viscosities, solubilities and sorption capabilities of the organic compounds present. In addition, transformation of oil compounds by biochemical, microbiological, chemical and photochemical processes occurs simultaneously.

Transport in soils and groundwater. Water movement in the unsaturated soil zone, above the groundwater level, is mainly vertical and normally slow. The chemical condition is usually aerobic and frequently acidic in tropical soils. There is potential for sorption and biodegradation of hydrocarbon compounds mainly in the humic soil horizon. Most of these processes occur at their highest rates in the more biologically active upper soil zone, because of higher oxygen concentrations, content of organic matter and the much larger bacterial population (Chapman 1992).

In sandy soils of sufficient permeability, the fraction of mobile hydrocarbons like benzene may find its way to shallow aquifers. Solutes are transported by the bulk movement of the flowing groundwater, a process termed advection. When petroleum products are released into an aquifer they will spread out from the expected advective flow path and form a contaminant plume which broadens along and perpendicular to the flow direction (Lawrence & Foster 1987). The main operative process is mechanical dispersion which arises from the tortuosity of the pore channels in a granular aquifer, e.g. alluvial sands. When pollutants, like most hydrocarbons, are not water soluble, they enter aquifers in the immiscible phase. In this case, transport is governed by factors different from those which determine solute groundwater flow, notably the density and viscosity of the immiscible fluid.

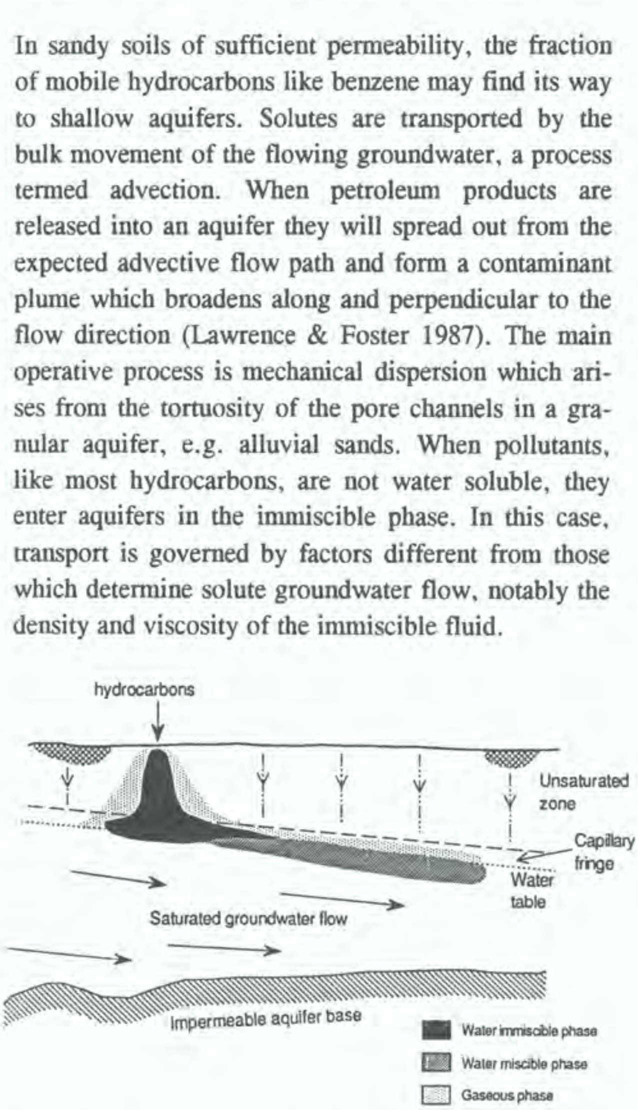

Fig. 9. Generalized distribution of hydrocarbon phases down a groundwater gradient following a surface spillage (after Lawrence & Foster 1987).

Fig. 9. Migración y difusión esquemática de hidrocarburos de un derrame en el agua subterránea.

Crude oil compounds are less dense and more viscous than water. Due to the density difference, they tend to float at the water table (Fig. 9) and subsequent lateral migration depends on the hydraulic gradient. In this position they can rise with the rising water levels, and during subsequent recession, the hydrocarbons may be held by surface tension effects in the pore spaces of the unsaturated zone above the groundwater table. Given sufficient porosity of the aquifer, the immiscible hydrocarbon phase can displace water from the porous matrix. This is controlled by the surface tension properties of the immiscible fluid relative to water. Once in the aquifer, an immiscible body of dense solvent could act as a buried pollution source for a long time. The rate of removal will depend on the rate of groundwater flow, microbial activity, availablity of oxygen and nutrients in the groundwater, and others.

4.4. Formation Waters

In an oil reservoir, formation water generally is present in two forms: as free flowing water (bottom or edge water) and as interstitial water.
The first can be understood as a fossile groundwater which occupies the pores in the host rock adjacent to an oil accumulation. Only a minor part of the porous medium is filled with oil and gas, the much larger part of the filling being water. Interstitial water is found within the oil reservoir. The water is being kept by capillary forces or by adsorption. Formation waters may have their origin from sea water which has been entrapped in the pores of marine sediments or they migrated from other sources within the sedimentary sequence.

Their content of salts is derived from the intense leaching of minerals from a huge volume of porous host rock, typically sandstones, by the circulating groundwaters. Rare elements may accumulate in formation waters which form easily soluble salts like cesium and rubidium (alkaline metals) or bromine and iodine (halogenids), but which are present in rocks in extremely low concentrations. Trace metals like nickel, vanadium and copper, which occur in crude oils, may also be found in significant concentrations in reservoir waters.

Formation waters in contact with a petroleum reservoir are saturated with water-soluble hydrocarbons like benzene, naphthalene and their methylated isomers.

5. Crude Oil Production in the Oriente

5.1. Characterization of the Oils

API gravities of crude oils in the Oriente generally range between 10° and 35° API, although the major part of the production is of 26° to 32° (see section 3.1.). Heavy oils of 10° to 25° are found in the eastern and southern areas of the Oriente basin (Smith 1989). Analytical data for a medium crude oil from the Sacha field are presented in Tables 2 and 3.

Parameter	Value
Gravity, °API	27.1
Specific Gravity	0.8922
total sulfur, wt.%	1.12
total nitrogen, wt.%	0.24
Conradson carbon residue (CCR), wt.%	7.07

Table 2. Analysis of some standard parameters of a typical Oriente crude oil (source: *Dirección Nacional de Hidrocarburos*).

Tabla 2. Análisis de algunos parámetros estandar de un crudo típico del Oriente (fuente: *Dirección Nacional de Hidrocarburos*).

In the present study, four different oils were sampled from Oriente fields and employed in the evaporation and biodegradation trials:

1. Shushufindi oil of 30.4 °API (specific weight 0.873 g/cm^3), a medium crude, sampled from central production facility (CPF) Shushufindi Central

2. Sacha crude, slightly heavier than the Shushufindi oil, of 28.8 °API (0.882 g/cm^3), CPF Sacha Central

3. Shuara oil, a heavy crude collected from well #27 in the Shuara field, of 10.3 °API (0.996 g/cm^3)

4. A sample provided by *Elf* from their Sunka-Wanke field of 21.1 °API (0,926 g/cm^3)

The concentrations of some hydrocarbon compounds in the crude oils are given in Table 4.
The saturate and aromatic profiles obtained by GC analysis of fresh Sacha crude oil are shown in Fig. 10.

5.2. Hydrochemistry of Formation Waters

The salinity of formation waters in the subandean basin of the Oriente ranges between 0.05 and 13 wt% eq. NaCl. The value generally increases towards the deepest parts of the basin and from the base to the top of the sedimentary sequence. The salt content of formation water of the Sacha main field is exceptionally low with only 0.05% NaCl (Smith 1989).

The formation waters analyzed were sampled from the "wash tank" in the central production facilities.

Fraction	Yield	S_t	N_t	Ni	V	CCR	Asphaltenes
	L.V.%	wt.%	wt.%	ppm	ppm	wt.%	wt.%
Off gas (light end)	1.4	<.0001	nd	nd	nd	nd	nd
IBP - 93° C	5.0	<.0001	nd	nd	nd	nd	nd
93° - 204° C	16.0	0.0210	nd	<.1	<.1	nd	nd
204° - 260° C	9.0	0.21	nd	nd	nd	nd	nd
260° - 327° C	12.4	0.64	0.009	nd	nd	nd	nd
327° - 538° C	30.8	1.30	0.094	0.1	0.1	0.14	1.30
>538° C	25.4	2.29	0.68	158	432	26.8	18.6

Table 3. Liquid volume percentages, total sulfur and nitrogen, nickel and vanadium, Conradson carbon residue and asphaltenes in different distillation fractions of Oriente crude oil. Temperature ranges converted from degrees Fahrenheit (source: *Dirección Nacional de Hidrocarburos*).

Tabla 3. Porcentaje del volumen de líquido, contenido de azufre y nitrógeno total, niquel y vanadio, residuo de carbón Conradson y asfaltenos en diferente fracciones de destilado del crudo del Oriente. Rangos de temperatura convertidos de grados Fahrenheit (fuente: *Dirección Nacional de Hidrocarburos*).

Compound	Shushufindi	Sacha	Elf	Shuara
	mg/L			
Isopropylbenzene	1400	804	711	727
Propylbenzene	2100	1520	1310	962
Naphthalene	602	560	525	590
n-Dodecane	4463	2760	1807	1209
n-Pentadecane	7131	3990	2296	1516
n-Hexadecane	4671	2390	1714	1297
Pristane	2517	2066	1311	1010
Phytane $+C_{18}$ alkane	6075	6107	3197	1872
Residue unsoluble in cyclohexane	8.90%	7.45%	9.80%	64.9%

Table 4. Concentrations of some hydrocarbons identified by capillary gas chromatography in four crudes used in laboratory trials.

Tabla 4. Concentraciones de algunos hidrocarburos identificados por cromatografía capilar en cuatro crudos usados en las pruebas de laboratorio.

Because the produced oil is received from a large number of wells within the oil field, the separated co-produced water usually is a mixture of waters from different geological formations. Hence it is not possible to use the analyses to chemically distinguish between the brines from the Hollin and the Napo Formations.

Analytical results for 15 samples of formation waters are shown in Table 5. The major cations Na, K, Ca, Mg, Sr, Ba and the anions Cl and Br are highly correlated to the total salt content expressed as conductivity. It can be calculated from mole equivalents (milliequivalents) that around 90% of solute content is NaCl.

Ammonium (NH_4^+), the only reduced species measured, is also related to salinity (Fig. 11).

No relationship is observed between conductivity and bicarbonate (HCO_3^-) content (Fig. 12). Leaving one outlier aside, HCO_3^- values are fairly constant in all samples. There is also no correlation between calcium

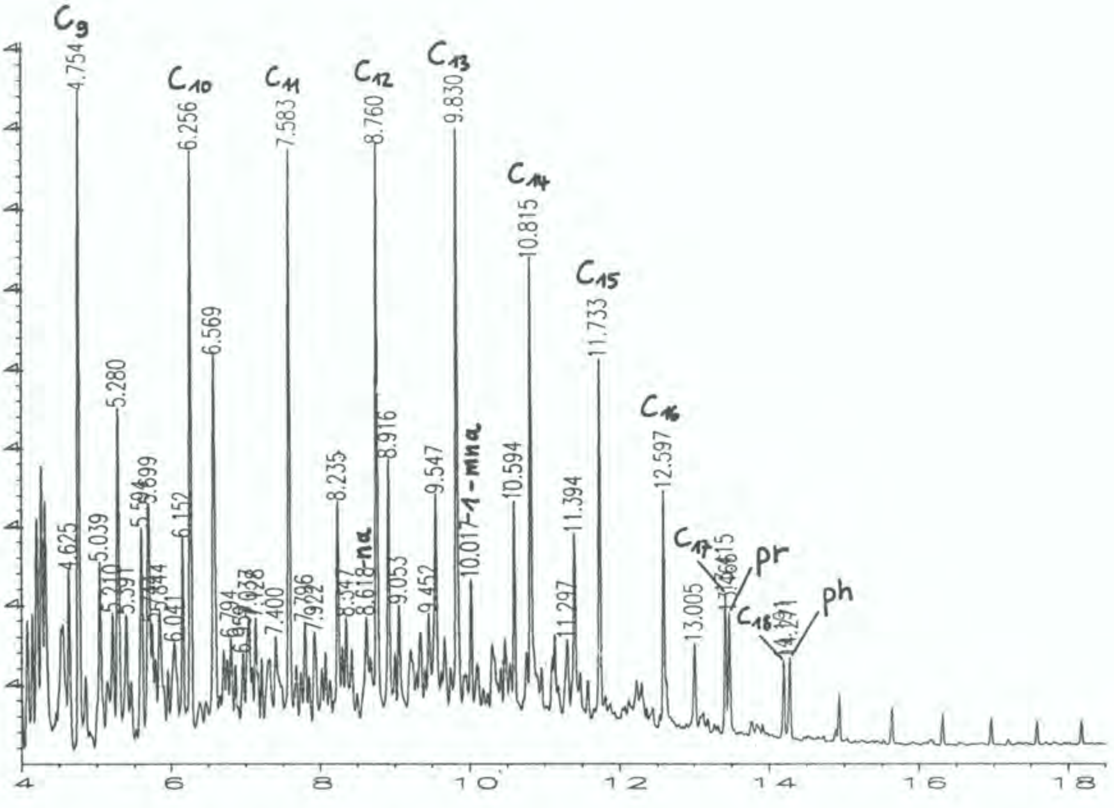

Fig. 10. Gas chromatography (GC) diagram of fresh Sacha crude oil. x-axis = retention time on the GC column in minutes; y-axis = peak magnitude; C_9, C_{10}, C_{11} etc. = n-alkanes with number of carbon atoms; s.i. = solvent impurity; na = naphthalene; 1-mna = 1-methylnaphthalene; pr = pristane; ph = phytane.

Fig. 10. Cromatograma de crudo fresco del campo Sacha. eje de abscisas = tiempo de retención en la columna de cromatografía de gases (CG) en minutos; eje de ordenadas = magnitud del pico; C_9, C_{10}, C_{11} etc. = n-alkanos con número de átomos de carbon; s.i. = impureza del solvente; na = naftaleno; 1-mna = 1-metilnaftaleno; pr = pristano; ph = fitano.

Sample #	Location	Temp	pH	Cond.	Oxy.	Na	K	Ca	Mg	Sr	Ba	P	Fe	Mn	Zn	HCO3	NH4	SO4	Cl	Br	F	r.o.
		°C		mS/cm	%	mg/l					µg/l		mg/l	µg/l		mg/l						
1/5.3.	Est. Shushufindi SW entrada 1° piscina	36	7	68.9	nd	15100	321	2520	364	166	14300	645	12.7	786	<5	318	34	79.2	27800	123	0.1	287
2/5.3.	Est. Shushufindi SW salida campo	nd	7.4	66.8	22	14700	323	2430	345	159	13900	457	11.9	815	132	330	35	53.5	27500	124	0.1	nd
3/5.3.	Est. Shushufindi C salida 1° piscina	nd	7.3	50.1	nd	10600	315	1670	213	86	5040	448	5.55	741	32	nd	36	106	19100	83.2	0.2	10
4/5.3.	Est Shushufindi C piscina reinyección	nd	7.5	43.3	nd	9440	298	1140	170	71	3630	<50	3.63	198	<5	161	7.5	107	16700	70	0.2	12
5/5.3.	Est. Shushufindi S wash tank	37	7.2	60.5	nd	13300	289	2050	277	129	10200	159	16	455	<5	214	27	73.6	24300	106	0.2	8
3/6.3.	Est. Pichincha wash tank	nd	7.3	35.4	nd	7860	347	1050	172	59.1	2430	<50	5.58	353	<5	254	19	270	12900	49.7	0.2	189
4/6.3.	Est. Shushuqui wash tank	nd	6.9	67.1	nd	14800	250	2550	333	136	5980	207	27.6	1140	45	nd	33	184	28400	122	0.2	132
5/6.3.	Est. Shuara wash tank	nd	6.9	51.3	nd	11300	347	1400	199	85.3	5280	<50	21.7	1290	471	182	32	33	20300	83	0.6	7
6/6.3.	Est. Secoya wash tank	nd	7.2	55.9	nd	11900	315	1860	306	102	6570	<50	15.5	798	<5	300	28	178	21900	93	0.2	4
4/7.3.	Est. Sacha N2 wash tank	nd	7.4	4	nd	543	65.5	218	30.3	8.49	860	93	0.17	13	13	nd	0.9	50.6	962	3.4	2.3	706
5/7.3.	Est. Sacha N2 riachuelo finca 200 m abajo Est.	33.5	7.1	4	30	534	61.9	348	29.2	8.7	1120	109	1.34	311	12	253	0.7	47.3	923	3.2	2.2	212
6/7.3.	Est. Sacha C wash tank	nd	7.1	16.2	nd	3170	114	530	49.1	23.2	3410	<50	3.71	203	51	175	13	10.5	5880	25	2.2	55
1/8.3.	Est. Auca C wash tank	nd	6.8	33.8	nd	7300	83.5	858	128	66.3	7900	544	2.88	580	<5	366	16	21.1	12700	52.8	1.9	56
3/9.3.	Est. L. Agrio N wash tank	nd	7.3	19.3	nd	3500	213	765	62.6	38.5	1440	3560	0.84	601	<5	1280	12.5	33.6	6980	25	0.9	42
1/26.4.	Campo Elf wash tank	nd	7.7	61.6	nd	13580	76	1422	194	72.5	2950	nd filt.->	15.4 0.4	1310 1290	<10	281	31	154	24600	97	nd	163

r.o. = residual oil; nd = not determined

Table 5. Analytical data of formation waters sampled from Oriente oil fields after crude oil separation.
Tabla 5. Datos analíticos de aguas de formación de algunos campos de crudo en el Oriente.

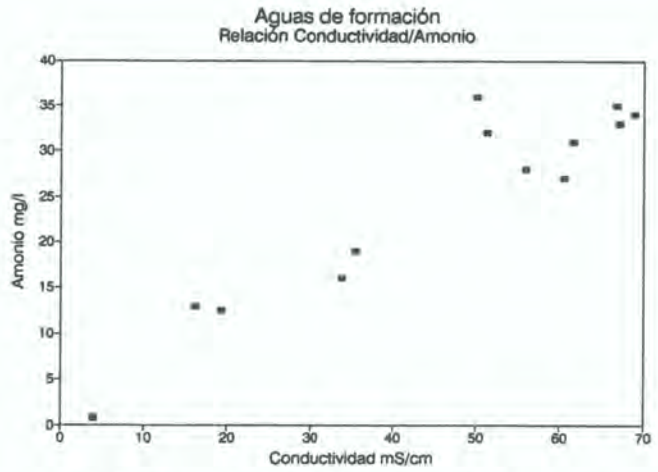

Fig. 11. Scatter plot for conductivity against ammonium in formation waters of Oriente oil reservoirs.

Fig. 11. Diagrama de la conductividad contra amonio en aguas de formación de los reservorios de crudo en el Oriente.

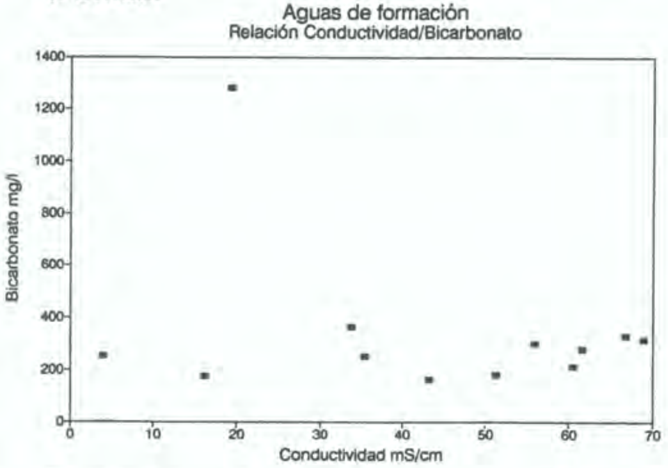

Fig. 12. Scatter plot for conductivity against bicarbonate in formation waters of Oriente oil reservoirs.

Fig. 12. Diagrama de la conductividad contra bicarbonato en aguas de formación de los reservorios de crudo en el Oriente.

and bicarbonate. The content of sulfate (SO_4^{2-}) is variable and independent of the total salt concentration.

Trace metals in some samples were analyzed by highly sensitive ICP-MS. Results are shown in Table 6.

Nearly all metals are positively correlated with conductivity, i.e. concentrations rise with increasing solute content. The alkaline metals rubidium and cesium are an exception and are correlated with potassium (compare with Table 5). The elements nickel, vanadium, and, to some extent, selenium are typically enriched in the form of organic compounds in crude oil and are also found in considerable concentrations in formation waters. Selenium probably is present in anionic form (selenite and selenate oxyanions).

The presentation of element concentrations as mole equivalents (milliequivalents) in a number of formation waters in the "Schoeller" diagram (Fig. 13-15) illustrates the similarity in chemical composition of the brines. Concentrations of alkaline and earth alkaline metals, chloride and bromide vary only in relation to the total salinity of the solution (the curves in this part of the diagram are parallel). Sulfate values are highly variable relative to the other ions. Sample 4/7.3. from the Sacha field (Sacha Norte 2) in Fig. 14 is obviously distinct from the other formation waters. It has the lowest conductivity of all formation waters, but both sulfate and bicarbonate contents are of the same order of magnitude as in the other samples. The highest sulfate value (270 mg/L) was measured in sample 3/6.3. from the Pichincha field. The water had a turbid black colour when taken from the separation vessel, whereas most other waters were clear at the moment of sampling. This observation raises the ques-

Sample	Cond.	Cu	Pb	Cd	Cr	Ni	Se	V	Rb	Cs	K
	mS/cm	µg/L									
5/7.3.	4.0	<10	<1	<1	<10	21	33	327	219	32	62
3/9.3.	19.3	<10	<1	<1	<10	10	52	532	681	82	213
5/6.3.	51.3	<10	<1	<1	12	72	400	1070	799	39	347
1/26.4.	61.6	13	45	<1	18	71	230	1170	139	16	76
Guideline[*]		*2*	*2*	*0.8*	*2*	*65*	*1*				

[*] Canadian guidelines for the protection of freshwater aquatic life (CCREM 1987)

Table 6. Analytical data for some relevant trace metals in formation waters from Oriente oilfields (values in µg/L).

Tabla 6. Datos analíticos de algunos metales en aguas de formación de campos petroleros en el Oriente (concentración en µg/L).

tion whether the original chemical composition of the formation waters may be modified by chemical reactions which take place in the production facility.

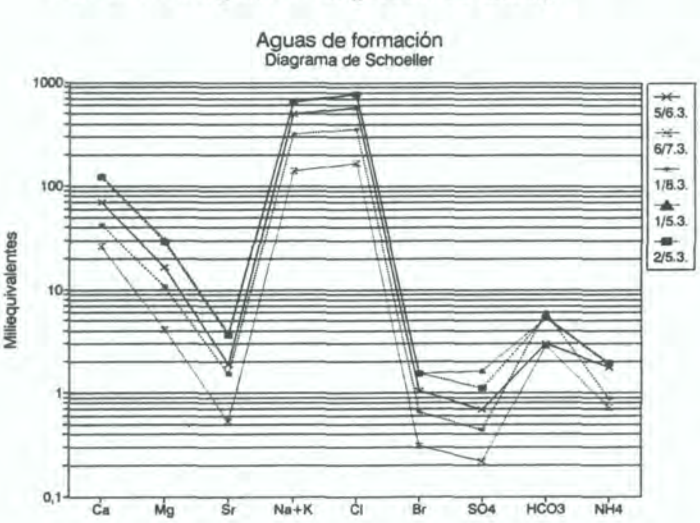

Fig. 13. Schoeller diagrams (major elements in milliequivalents) for formation waters from Shuara, Sacha, Auca, and Shushfindi oil fields in the Oriente.

Fig. 13. Diagrama de Schoeller (elementos mayores en miliequivalentes) de las aguas de formación de los campos Shuara, Sacha, Auca y Shushufindi en el Oriente.

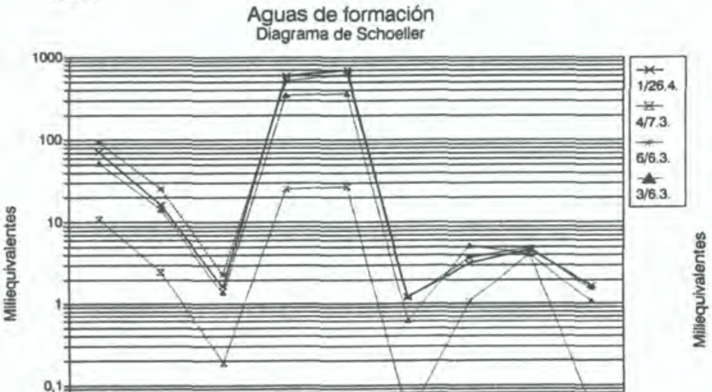

Fig. 14. Schoeller diagrams (major elements in milliequivalents) for formation waters from Sunka-Wanke, Sacha Norte, Secoya and Pichincha oil fields in the Oriente.

Fig. 14. Diagrama de Schoeller (elementos mayores en miliequivalentes) de las aguas de formación de los campos Sunka-Wanke, Sacha Norte, Secoya y Pichincha en el Oriente.

Activity of sulfate-reducing bacteria. Physiochemical (temperature and pressure decrease, degassing) and biochemical (microbial activity) changes may affect the composition of the formation waters. This is most evident in the case of sulfate. Sulfate reducing bacteria (SRB) are a notorious problem in the production process. In some cases, the freshly sampled solution from the wash tank was transparent but turned black within a few minutes in the sampling vessel. The finely dispersed black particles presumably consist of metastable iron sulfide (FeS), which immediately forms upon (minimal) aeration of the brine. A few hours later, the black suspended matter settles on the bottom and changes colour to orange brown. The residue is easily soluble in nitric acid, which is characteristic for iron oxyhydrates, $Fe(OH)_3$. Because sulfate is released when the labile iron sulfide is oxydized to iron oxyhydrates (in the aerated sample), the measured sulfate concentration depends on the amount of iron sulfide which was originally in the sample. Due to the fact that large colonies of SRB exist in the pipelines and separation vessels (oral comm., *Petroproducción* staff), a large percentage of sulfate originally present in the formation waters is reduced to sulfide species. Therefore, the dissolved sulfate content measured in the samples is mainly controlled by the extent of bacterial activity in the treatment plant and the amount of iron sulfide which was collected in the water sample from the wash tank.

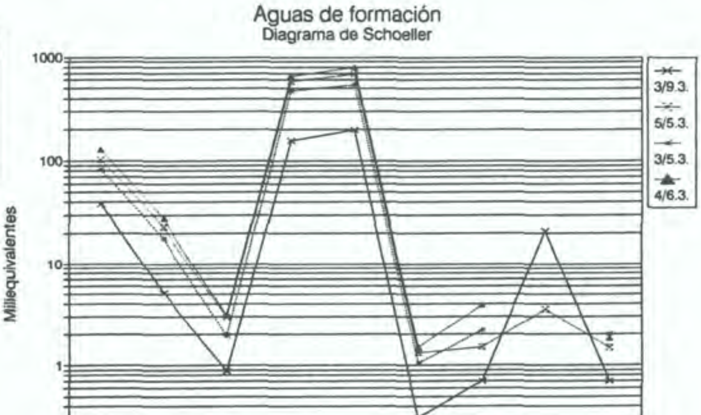

Fig. 15. Schoeller diagrams (major elements in milliequivalents) for formation waters from Lago Agrio, Shushufindi and Shushuqui oil fields in the Oriente.

Fig. 15. Diagrama de Schoeller (elementos mayores en miliequivalentes) de las aguas de formación de los campos Lago Agrio, Shushufindi and Shushuqui en el Oriente.

SRB reduce sulfates in a dissimilatory fashion (also termed sulfate respiration), an energy-yielding process where sulfate acts as the terminal electron acceptor, the final product being sulfides. SRB require not only anaerobic conditions, but a reducing environment with a redox potential of -150 mV. The damaging effect of SRB on iron and steel pipeworks and tanks results from the coupling of electrochemical corrosion of iron with bacterially mediated sulfate reduction through electron transfer. The overall reaction is:

$$4\,Fe + SO_4^{2-} + 2\,H_2O + 2\,H^+ \rightleftharpoons FeS + 3\,Fe(OH)_2$$

The sulfide anion (S^{2-}) produced has itself a corrosive action on the metal.
The control of SRB is difficult because they are able to colonize the most inhospitable environments, and they resist or tolerate many biocides.

5.3. Description of the Extraction Process

Once the exploration drilling has been successful and commercially extractable reserves have been established, production begins. Simple earthen pits for the storage of drilling muds and crude oil from well tests were used in the former *Texaco* fields which are now exploited by *Petroproducción*. Today, drilling muds and oils are separately stored in lined pits. Oil and grease is removed from the pit surface, usually with a skimmer pump. After sedimentation of the coarse solids, the remaining suspended matter is treated in a flocculation process and the remnant water neutralized. The purified water is discharged and finally the pits are filled up and covered. Produced crude from well tests is transported to the central production facility.

Dry wells are sealed with cement to avoid the rise of highly saline formation waters which may contaminate upper groundwater horizons. In productive wells, a steel casing is sunk into the borehole and the remaining space between the casing and the well bore walls is filled with cement. The casing wall is perforated where it passes through the producing formation which enables the free flow of the oil to the surface. The wellhead ("christmas tree") fitted to the casing's end on the surface controls the flow rate and pressure of the well.

Recovery of oil from the reservoir depends on the geological conditions, reservoir pressure, properties of the oil and the exploitation technique. In the Oriente fields, free artesian flow of oil to the surface is rare. When there is sufficient co-produced gas in the crude oil, gas can be injected into the well, known as gas lift. Other techniques used for primary recovery are electric submersible pumps ("esps") placed at some depth in the well, and hydraulic pumping with crude oil (power oil). Flooding and pressurizing the depleted reservoir with reinjected formation water (water flood) is a secondary recovery method employed in some fields of *Petroproducción*.

The fluid which flows from the well is a mixture of oil, gas and water ("wet oil"). At the well platforms, chemicals such as corrosion inhibitors, antiscale, demulsifiers etc. are injected into the lines in which the produced petroleum is pumped to the central production facility (CPF). At the CPF, the crude oil lines from a number of wells are received in the manifold from where the liquid passes on to a three-phased separator. Before the original mixture enters the separation process, it is dosed with chemicals, mainly demulsifiers, scale and corrosion inhibitors and bactericides/biocides. In the CPFs operated by *Petroproducción* (most of them built by *Texaco*), the separators are mainly biphasic, i.e. only the gas is separated from the oil-water mixture. The gas obtained is frequently used as fuel in the production process. The oil flows on to a degassing tower and then enters the wash tank in which water and oil are separated. The produced water is discharged to decantation ponds which permit the partial recovery of floating oil.

In modern operations (taking as an example the CPF of *Occidental Petroleum of Ecuador* close to Limoncocha), the co-produced water which leaves the three phase separators flows to the heater treaters (82 °C) to separate any remaining oil and heat up any oil retrieved from pits or the reject tank; the water finally has an oil content of about 24 ppm. The crude oil is submitted to electrostatic desalination/dehydration vessels where the oil can be "washed" with freshwater (5-10% of water relative to the volume of oil). The dewatered petroleum which leaves this stage has a water content below 1% and less than 5 kg of salt in 1000 barrels of oil. The crude then passes through degassing towers and is stored in tanks with a capacity of two days of production to be exported through the main overland pipeline.

The co-produced water obtained in the various separation stages is collected in a skimming tank where the floating oil is removed continuously. In a second process, the water flows through "wemco" filtration units to remove emulsified oil, suspended solids, insoluble hydrocarbons and solids. The water with an oil content of 3-5 ppm finally is stored in tanks, ready for reinjection after dosing with chemicals. These chemicals are needed to control mineral scale build-up, corrosion, growth of micro-organisms and to eliminate residual oxygen.

Corrosion due to highly saline and aggressive formation waters and bacterial activity (sulfate-reducing bacteria) are major problems in the CPF. Corrosion is monitored by chemical and biological analyses of the flow-through waters and by electronic detectors. It is combated by the use of resistant materials in the construction of tanks and pipework, internal and external coating with plastics and paints, cathodic protection and the admixture of chemicals to the flowing liquid.

In new projects, all pipelines are buried, which protects them against damage by falling trees or road accidents. Pipework is equipped with automatic shutdown valves which are fitted to the wellheads (christmas trees) and close the pipeline in case a drop in pressure should occur.

5.4. Data on Oil Production and Discharge of Formation Waters

5.4.1. Production History

After decades of exploratory activities by a number of multinational and national oil companies, exploration in the Oriente showed its first commercial success in 1967 with the discovery of the Lago Agrio field by a *Texaco-Gulf* consortium (Fig. 16), which triggered off a number of discoveries in the region. The State of Ecuador, through its *Corporación Estatal Petrolera Ecuatoriana* (CEPE), renamed in *Petroecuador* in 1990, later became a minority partner in the *Texaco* consortium and replaced *Gulf* in 1976, thus becoming the majority financial partner. *Texaco* operated the oil fields until 1990, when a subsidiary of *Petroecuador* assumed operational management of the facilities.

Fig. 16. Lago Agrio No. 01, the first productive well drilled in the Oriente, close to the Lago Agrio airstrip (Lago Agrio field, map in appendix A1).

Fig. 16. Lago Agrio No. 01, el primero pozo productivo en el Oriente, cerca del aerodromo Lago Agrio (Campo Lago Agrio, mapa en anexo A1).

Production history in Ecuador is as follows (Koch 1995):

1938: 0.3 Mt (million tons)
1950: 0.4 Mt
1965: 0.4 Mt
1970: 0.2 Mt
1973: 10.7 Mt
1975: 7.8 Mt
1980: 10.8 Mt
1985: 14.3 Mt
1995: 19.4 Mt (12.3 Mt exported)

Cumulative production by the end of 1990 was 220 Mt. Proven reserves by the end of 1994 were estimated at 235 Mt by the Ecuadorian Ministry of Energy and Mines (quoted in Cornejo 1995).

5.4.2. Current State of Petroleum Activities

Mean daily production in the Oriente in 1995 was 386,000 b/d. Production from January to August 1995 was 93.6 mio. b of which 74.4 mio. b or 79.5% was produced by *Petroproducción*; companies under service contract with *Petroproducción* supplied 17.8 mio. b or 19%, and the *Petroproducción-City* consortium 1,4 mio. b or 1.5% (Petroecuador 1995). The production was obtained from a total of 539 wells in the Oriente fields.

According to official figures, the total production of formation waters in the fields operated by *Petroproducción* is around 170,000 barrel per day, of which approx. 25,000 barrels are reinjected. A source from the *Dirección Nacional de Hidrocarburos*, however, indicated that in 1991 in all Oriente oil fields about 220,000 b/d of water was produced (water content of wet oil about 35%) and it is estimated that the figure rose to 300,000 b/d of water in 1995.

Block No.	Company (operator)	Concession area in ha	Production start	Production in barrel (1994)	Remarks
7	Oryx Ecuador Energy Co. (USA)	200,000	1991	5,993,132	
14	Elf Hydrocarbures Equateur (France)	200,000	1993	823,912	located partially in Yasuni National Park
15	Occidental Exploration & Production Co. (USA)	200,000	1993	7,348,706	located in Limoncocha Biological Reserve
16	Maxus Ecuador Inc./ YPF (USA/Argentina)	200,000	1994	10,500,000 (estimate for 1995)	located partially in Yasuni National Park/ Waorani Ethnic Reserve
NN	City Investing Co. (Bermudas/GB)	35,000	1975	1,630,405	located in Cuyabeno Faunistic Reserve
10	ARCO Oriente Inc. (USA)	200,000	?		production start depends on pipeline construction
NN	Petroproducción/ Petroecuador	around 1,400,000	1972 (former TEXACO fields)	117,188,413	some fields in protected areas

Table 7. Crude oil production in Oriente fields in 1994.
Tabla 7. Producción de crudo en los campos del Oriente en 1994.

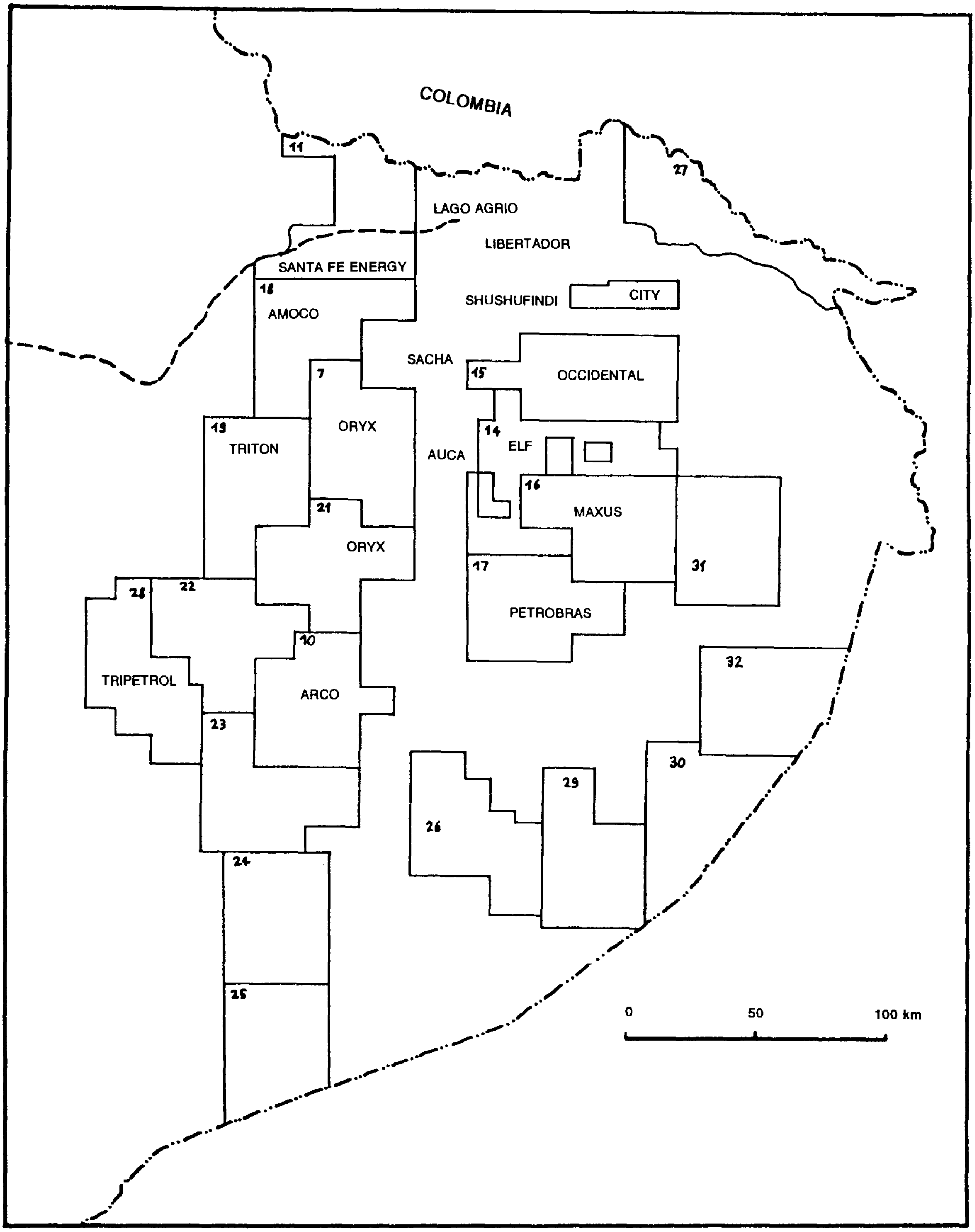

Fig. 17. Map of the Oriente region showing petroleum blocks in different stages of development in 1995 and major *Petroecuador* fields.

Fig. 17. Bloques petroleros en el Oriente en diferentes fases de desarrollo en 1995 y campos mayores de *Petroecuador*.

In 1995, a total of 20 designated blocks in four Ecuadorian Amazon provinces, covering an area of 3,835,000 ha (excluding the fields being exploited by *Petroproducción*) were in different stages of development (Fig. 17).

Out of these 20 blocks,
- six were actually producing or are in an advanced development stage; together with the area in which *Petroproducción* is operating, the total surface covered is 2,425,000 ha (Table 7);
- four blocks have been abandoned after exploration activities gave no positive result;
- four blocks out of the ten which were offered for bidding in January 1994 in the "Septima Ronda Internacional" received no offers;
- for six blocks of the Seventh Licensing Round, contracts have been signed in early 1995 between foreign petroleum companies and the State (Table 8).

The area under license by *Petroecuador* is about 2,000,000 ha, of which some fields have been taken out for international bidding.

Block No.	Company (operator)	Concession area in ha	Contract signed	Remarks
11	Santa Fe Petroleum (USA)	200,000	Jan/1995	borders Cayambe-Coca Ecological Reserve
18	AMOCO (USA)	200,000		includes site of the planned Sumaco National Park
19	Triton Energy Co. (USA)	200,000	Feb/1995	includes site of the planned conservation areas Sumaco and Napo Galeras
21	Oryx Ecuador Energy Co. (USA)	200,000	Mar/1995	partially located in Waorani Ethnic Reserve
27	City-Ramrod (GB/CAN)	200,000	Mar/1995	north of Cuyabeno Reserve, on the Colombian border
28	Tripetrol (Ecuador)	200,000	Feb/1995	

Table 8. Blocks for which exploration contracts have been signed during the Seventh Licensing Round in the Oriente.

Tabla 8. Bloques del Oriente cuyos contratos de exploración han sido firmados en la Séptima Ronda de Licitación.

6. Environmental Impact of Crude Oil Production in the Oriente

6.1. Surface Waters and Production Water Discharges

Analytical results obtained for waters sampled from creeks and streams in and around the periphery of oil producing areas of the *Oriente* (Table 9) show that in most of the waters the solute content (measured as conductivity) is very low, which is typical for watercourses in the rainforest draining highly weathered soils. The major dissolved compounds are calcium and sodium bicarbonate; chloride is very low. The mean Cl^- value for nine streams sampled in the present study is 3.5 mg/L, in four samples the value is below 1 mg/L. Some samples of waters of relatively high conductivity show a distinct chemical composition, the dominating anion being chloride (Fig. 18-19). These creeks are obviously affected by formation water discharges and reflect mixing of natural surface waters with formation waters at variable volume ratios from 50 to 350 (Table 10). The mixing ratio (V_Σ/V_{FW}) was calculated based on measured conductivity according to the equations:

$m_{FW} + m_B = m_{WS}$ (mass balance)
$V_{FW} + V_B = V_\Sigma$ (volume flow balance)
$(V_{FW} * c_{FW}) + (V_B * c_B) = (V_\Sigma * c_{WS})$

because $V_{FW} << V_B \Rightarrow V_B = V_\Sigma$

$(V_{FW} * c_{FW}) + (V_\Sigma * c_B) = (V_\Sigma * c_{WS})$
$V_{FW} * c_{FW} = V_\Sigma(c_{WS} - c_B)$
$V_\Sigma/V_{FW} = c_{FW}/(c_{WS} - c_B)$

where: **FW** formation water
WS surface water sampled
B natural background value for WS
V volume flow
V_Σ sum volume flow (in sampled watercourse)
c concentration expressed as conductivity

Analytical data from these samples also show an elevated content of barium, manganese, and, to a lesser extent, zinc (Table 11). These elements are typically associated with formation waters. The samples with the clearest impact of production waters were taken close to a production facility (1/6.3.), downstream of a fresh oil spill (6/5.3.) and close to unlined crude oil collection pits (2/6.3., highest Cl^- content, and 2/7.3.).

It is interesting to note that there was no visible surface drainage from the collection pits to the water bodies which were sampled. It appears that the liquids collected in unlined pits seep to shallow aquifers nearby. The water samples were taken at a distance of about 100 m (2/6.3.) and 250 m (2/7.3.) away from the open oil pits. The salt content in the subsurface seepage from oil pits probably originates from oil recovered from "wet oil" spills or poorly separated crude from production facilities.

The fact that saline waters penetrate the unlined oil pit walls indicates the permeability of the clayey soils. Although the extraction technique used in the present study was unsuitable to determine very low hydrocarbon concentrations in the collected water samples, it appears most likely that water-soluble oil components

Sample	Location (oil field)	$cond_{FW}$	$cond_{WS}$	$cond_B$	mixing ratio (total/formation water)
		mS/cm	mS/cm	mS/cm	(calculated)
2/6.3.	Shuara	51.3	0.920	0.07	60
1/6.3.	Secoya/Shuara	53.6	0.616	0.07	98
6/5.3.	Aguarico	57.9	0.242	0.07	337
2/7.3.	Sacha C	16.2	0.187	0.07	138
4/4.9.	Sacha N1	4.0	0.150	0.07	50

Table 10. Calculated mixing ratios for natural surface waters and formation waters in rainforest streams flowing through oil fields.

Tabla 10. Razón de mezcla calculado para aguas naturales y aguas de formación en cursos de agua cruzando por campos petroleros.

Sample #	Location	Temp	pH	Cond.	Oxy.	Na	K	Ca	Mg	Sr	Ba	P	Fe	Mn	Zn	HCO3	NH4	SO4	Cl	Br	F
		°C		mS/cm	%	mg/l					µg/l		mg/l	µg/l		mg/l					
2/9.3.	río Teteye abajo derrame (finca) 14 km de L. Agrio	25.2	6.4	0.093	79	9.72	0.6	8.27	2.43	0.17	35	<50	1.03	<5	9	51	<0,2	<0,5	5.8	<0,5	<0,1
3/7.3.	río Yanaquincha/ pozo Sacha 54	24.7	6.3	0.128	71	13.2	2.6	11.5	4.74	0.21	34	97	1.09	70	<5	74	<0,2	0.9	6.7	<0,5	<0,1
2/4.9.	riachuelo cerca Est. Sacha Sur	23.2	6.6	0.079	82	4.38	2.1	7.82	4.47	0.13	15	<50	0.2	9	<5	45	nd	1.12	0.77	<0,05	<0,1
3/4.9.	río Yurac Quincha Campo Sacha	23.8	6.9	0.145	82	6.96	2.2	13.7	6.87	0.18	11	144	0.38	21	6	88	nd	0.98	0.76	<0,05	<0,1
7/6.3.	Piscina vieja pozo Shuara 05	nd	6.2	0.08	nd	6.97	<0,4	8.92	0.84	0.13	203	<50	1.14	120	7	nd	<0,2	nd	nd	nd	nd
1/7.3.	riachuelo/derrame cerca de pozo 60 Campo Sacha N1	25	6.4	0.08	51	13	11.2	5.26	1.49	0.17	62	<50	0.62	11	7	34	<0,2	3.5	6.7	<0,5	<0,1
2/8.3.	río 300 m abajo piscina recup. pozo Auca 26	24.3	5.6	0.027	90	4.55	<0,4	3	0.75	0.07	50	<50	0.41	6	14	23	<0,2	<0,5	0.7	<0,5	<0,1
3/8.3.	piscina vieja Anaconda 01	nd	6.2	0.055	nd	9.35	1.3	2.78	0.77	0.05	40	<50	1.81	35	91	nd	<0,2	nd	nd	nd	nd
1/4.9.	río Napo/ San Carlos	20.2	7.6	0.094	88	4.47	2	13.4	4.52	0.08	24	<50	<50	<5	33	48	nd	11.9	2.29	<0,05	<0,1
4/8.3.	río Aguarico puente L. Agrio - Sacha	22.7	6.3	0.107	100	4.9	0.9	18.4	1.92	0.12	414	<50	0.62	25	48	64	<0,2	7.5	0.9	<0,5	0.1
1/9.3.	río Teteye cerca pozo 02 Campo L. Agrio	24.7	6.2	0.116	87	12.7	1.5	9.85	3.53	0.22	34	<50	1.07	<5	5	66	<0,2	0.9	7.5	<0,5	<0,1

Table 9. Analyses of natural waters in the periphery of Oriente oil fields unaffected by oil production wastewaters.
Tabla 9. Análisis de aguas naturales en la periferia de los campos de crudo del Oriente no afectados por la producción petrolera.

like monoaromatics leak from the pits and contaminate subsurface and surface waters.

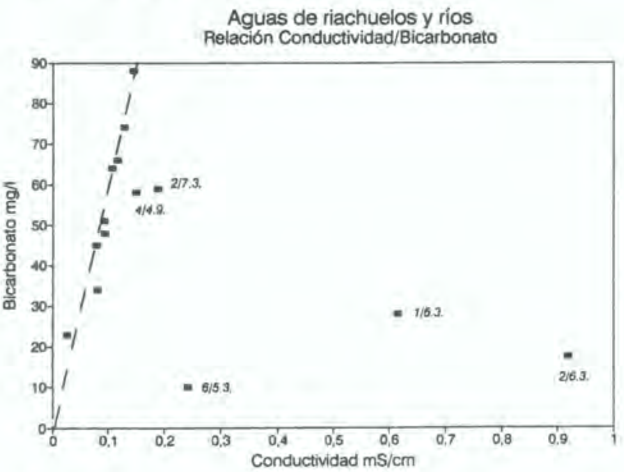

Fig. 18. Scatter plot for conductivity against bicarbonate in waters from streams and rivers of the Oriente. The broken line highlights the correlation of conductivity and bicarbonate in watercourses unaffected by petroleum production discharges.

Fig. 18. Diagrama de la conductividad contra bicarbonato en aguas de riachuelos y ríos del Oriente. La línea cortada resalta la correlación de la conductividad y del bicarbonato en los cursos de agua no afectados por las descargas provenientes de la producción petrolera.

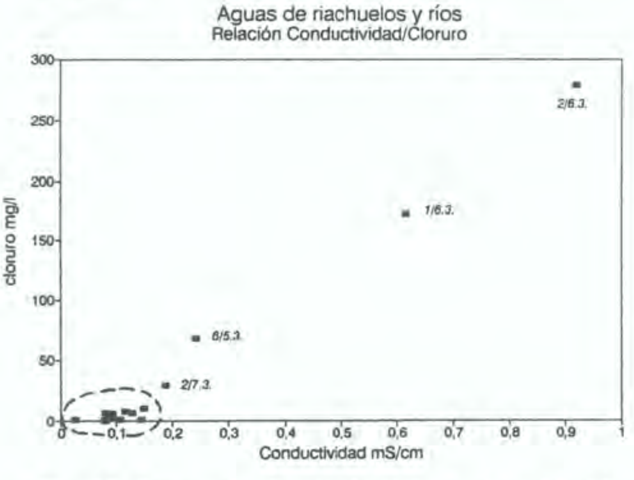

Fig. 19. Scatter plot for conductivity against chloride in waters from streams and rivers of the Oriente. The encircled data points are from water samples unaffected by production discharges.

Fig. 19. Diagrama de la conductividad contra cloruro en aguas de riachuelos y ríos del Oriente. Los datos encerrados en círculos provienen de muestras de aguas no afectadas por descargas de producción petrolera.

Measurements of residual oil content in formation waters sampled from *Petroecuador* production facilities (Table 5, last column) give a mean of 144 mg/L (13 measurements). The values range from 4 mg/L, indicating an optimized separation process, to 706 mg/L, showing a very poor and inefficient treatment.

Formation waters discharged from installations of the former *Texaco-Petroecuador* consortium, about 170,000 barrel per day, frequently show a visible oil film (Fig. 20). Assuming a mean petroleum content of about 150 mg/L and no polishing of the production discharges, up to 25 barrel or 4000 litres of crude may enter local streams and rivers daily.

6.2. Behaviour and Fate of Crude Oil in the Tropical Environment

6.2.1. Evaporation Trials

Three different crude oils of the *Oriente* and n-dodecane as a reference substance were studied in a laboratory evaporation experiment at 30 °C (see section 2.2.). The results show an approximately exponential decrease in weight in the first few days of the experiment and a slow linear decrease in the following period (Fig. 21a,b). The overall pattern is a composite of a number of linear evolution trends with different slopes controlled by the specific evaporation rate of individual compounds. The lighter oils have higher concentrations of n-alkanes of low molecular weight and monoaromatics (compare with Table 4).

In the case of the Shushufindi oil (30.4 °API), 21% of the oil evaporated within the first three days, while the total loss was only 30% after 80 days. The Sacha crude showed slightly lower losses. The Shuara oil, a heavy crude of 10.3 °API, gave a loss of only 13% in the period of 80 days.

In order to determine which substances were lost by evaporation, samples for GC analysis were taken on days 2, 5, 14 and 43 of the laboratory trial.

Volatile monoaromatics such as isopropylbenzene and propylbenzene disappeared completely within the first 5 days. The concentration of dodecane and naphthalene diminished significantly during the sampling period. Naphthalene (a diaromatic compound) was below detection after 43 days, while the concentration of dodecane (saturated C_{12}-alcane) decreased in the range of 80-90% in the same period.

Compounds of higher molecular weight and boiling points and alkanes of longer chain lengths (e.g. hexa-

Sample #	Location	Temp	pH	Cond.	Oxy.	Na	K	Ca	Mg	Sr	Ba	P	Fe	Mn	Zn	HCO3	NH4	SO4	Cl	Br	F
		°C		mS/cm	%	mg/l					µg/l		mg/l	µg/l		mg/l					
1/6.3.	riachuelo entre Secoya y Shuara	24.7	6	0.616	57	125	1.9	23	3.85	1.29	151	<50	1.82	200	7	28	<0,2	2.2	172	<0,5	<0,1
2/6.3.	pantano abajo piscina recuperación Campo Shuara 09	27.5	5.6	0.92	50	158	3.5	21.3	2.95	0.89	324	<50	4.27	76	27	17.5	0.3	2.1	279	0.9	0.2
6/5.3.	Aguarico pozo 01 riachuelo 600 m abajo derrame	nd	5	0.242	nd	27.3	1.2	10.1	2.46	0.15	426	<50	0.66	870	20	10	<0,2	1.2	68.7	<0,5	<0,1
2/7.3.	riachuelo 250 m abajo de piscina pozo Sacha 98	23.6	5.9	0.187	nd	21.2	3.6	11	3.61	0.32	124	<50	1.97	280	25	59	<0,2	3.4	29.5	<0,5	<0,1
4/4.9.	río Yanaquincha/ Est. Sacha N1	24	6.7	0.15	83	10.7	2.5	11.8	5.36	0.19	17	93	0.47	20	<5	58	nd	0.98	9.85	<0,05	<0,1

Table 11. Analytical data of natural waters affected by oil production effluent discharges.

Tabla 11. Datos analíticos de aguas naturales afectados por las descargas de la producción petrolera.

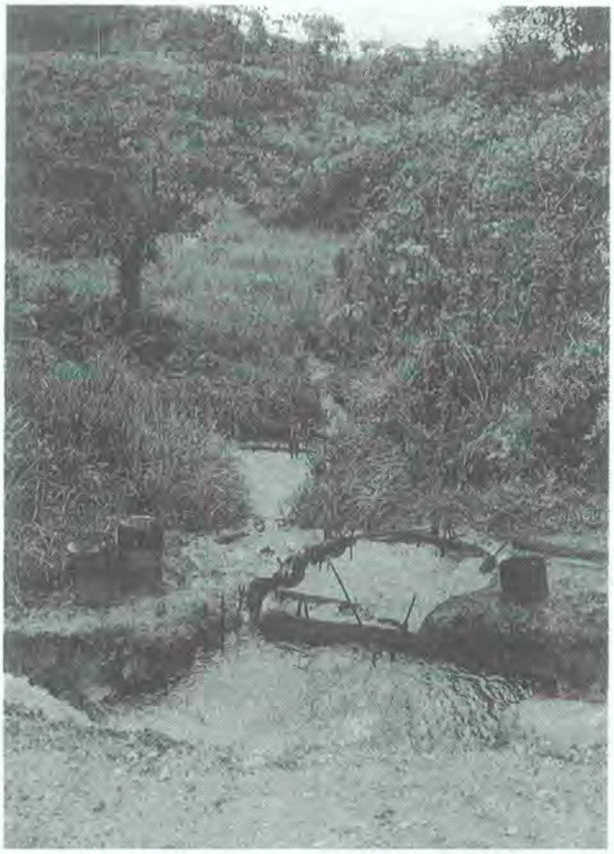

Fig. 20. Small creek close to the Secoya central production facility which receives production water discharges. Visible oil floating on the surface (Libertador field, map in appendix A1).

Fig. 20. Riachuelo desaguando descargas de producción (aguas de formación con trazas de petróleo) de la estación Secoya. Petróleo flotando en la superficie (Campo Libertador, mapa en anexo A1).

decane and pristane) show only a slow decrease in concentration. The boiling point of a specific hydrocarbon appears to be the best parameter to characterize its evaporation behaviour although the evaporation rate is influenced by other physical factors. Atlas (1975) observed in evaporation trials that hydrocarbon compounds above molecular weight 170 were lost very slowly.

Analyses of weathered oils from pits. Weathered oil was sampled from three production pits ("piscinas de producción") at wells No. 87 and No. 98 from the Sacha field and well No. 26 from Auca field. The unlined earth pits have been used for the dumping of drilling muds and fluids, and oils from well tests.

The oil from the abandoned Sacha No. 87 pit (the well was drilled in January 1980) is highly viscous; no fresh crude has been discharged into the pit for several

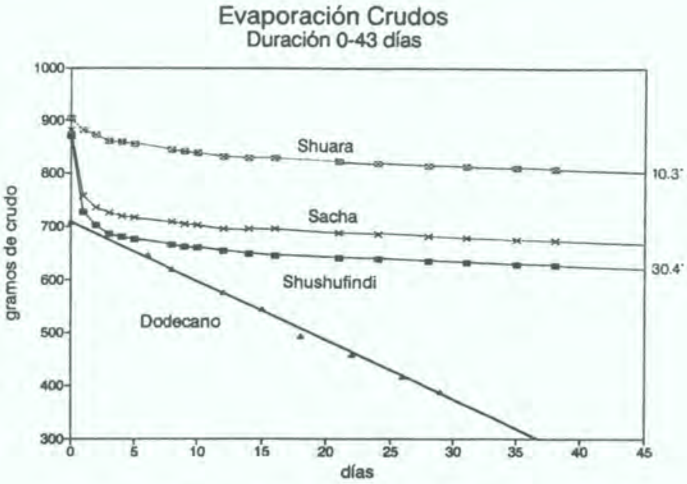

Fig. 21a. Weight loss of different crude oils and n-dodecane as reference substance during the evaporation trial from the start to day 43.

Fig. 21a. Pérdida de peso de diferentes crudos y n-dodecano como sustancia de referencia durante las pruebas de evaporación desde el inicio hasta el día 43.

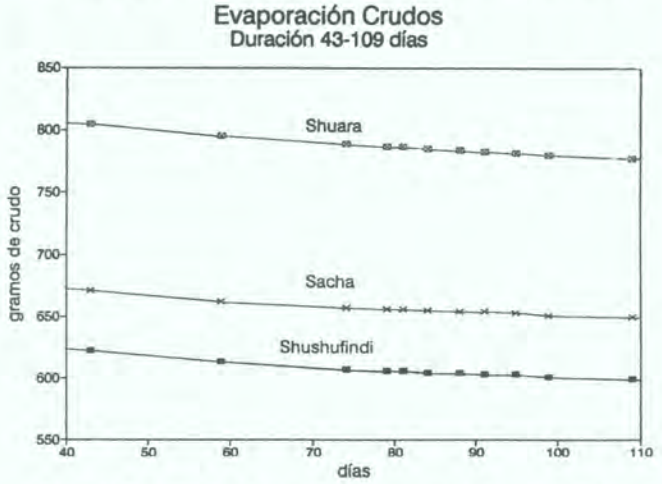

Fig. 21b. Weight loss of different crude oils during the evaporation trial, days 43 to 109.

Fig. 21b. Pérdida de peso de diferentes crudos durante los ensayos de evaporación, días 43 al 109.

years. The large pits at Sacha No. 98 (well sunk in April 1978) and Auca No. 26 are still being used for the collection and storage of weathered and degraded oils (Fig. 22). The sample from the pit at Auca No. 26 (approximate size of the pit: 20*70 m, depth 2 m) was taken from the far end away from the ramp where the degraded oils are dumped by trucks. The crude oil was similarly viscous as the Sacha No. 87 sample. Results of GC analysis of the oils (Fig. 23) showed a chemical composition similar to the highly viscous crude oils at the end (110 days) of the laboratory experiments, although monoaromatics where still detectable in the Sacha No. 98 sample.

Fig. 22. Waste oil collection pit at well No. 26 in the Auca field (location in map in appendix A1).

Fig. 22. Piscina de producción al lado de pozo No. 26, campo Auca, actualmente utilizado para la recolección de crudos viejos (localidad en mapa en anexo A1).

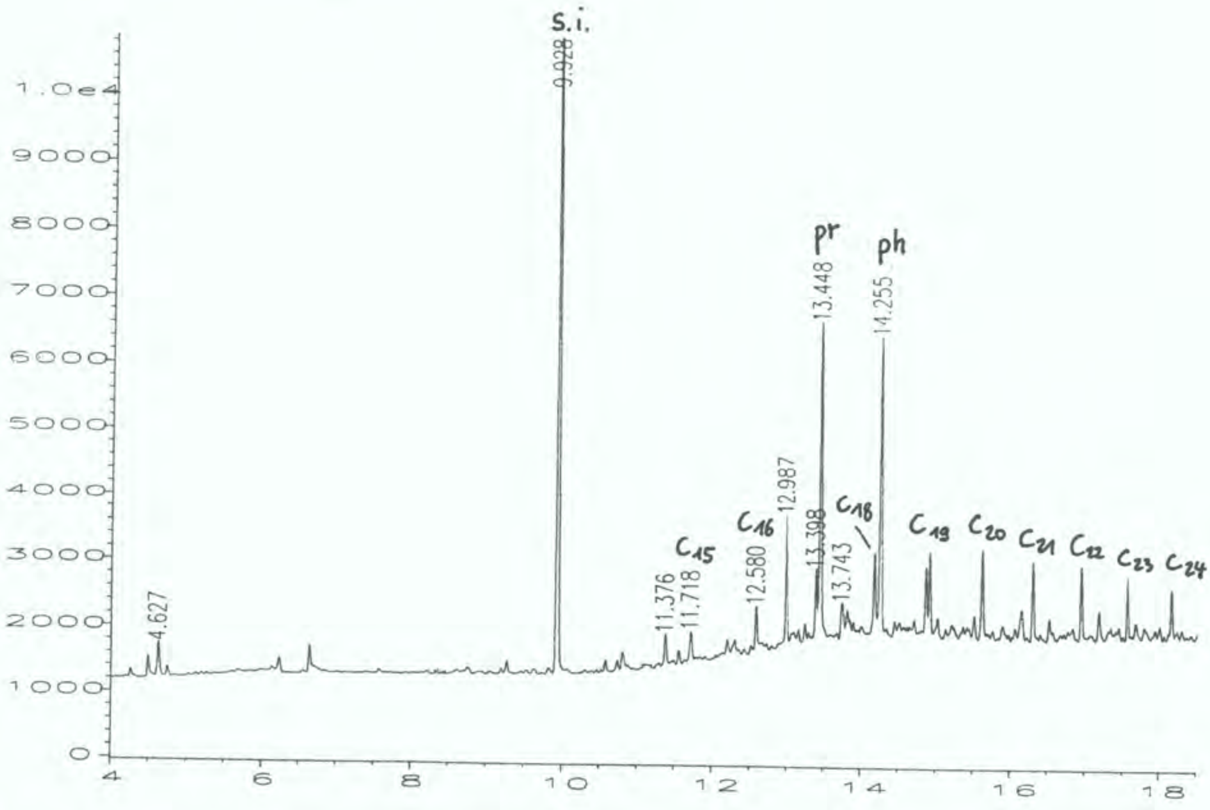

Fig. 23. Gas chromatogram of highly weathered oil from the pit at Auca No. 26. Volatile components with retention times below 10 minutes (x-axis) have disappeared completely, n-alkanes of longer chain length remain. The high concentration of pristane (pr) and phytane (ph) relative to the n-alkanes indicate microbial alteration of the oil.

Fig. 23. Cromatograma de crudo altamente degradado tomado de la piscina Auca No. 26. Compuestos volatiles con tiempos de retención menos de 10 minutos (eje de abscisas) desaparecieron completamente; n-alkanos con cadenas largas permanecen. La alta concentración de pristano (pr) y fitano (ph) relativo a los n-alkanos indican alteración microbiana del crudo.

Abandoned waste oil pits, most of them located in the former *Texaco-Petroecuador* concession, are a major environmental problem. A typical old pit, which was recently treated and cleaned, is at well Sacha No. 106. Its size was 80*30*2.5 m, holding about 15.000 barrels of highly weathered crude oil of 8-12 °API. It is estimated that more than one hundred open waste oil pits in the Oriente fields hold about 1.500.000 barrel of oil.

6.2.2. Biodegradation Experiments

In order to investigate the degradation of crude oil through autochthonous bacteria and fungi, experiments of 5 days duration under optimum and deficiency conditions (i.e. nutrient and oxygen limitation) were performed in the laboratory (Fig. 24). Minute quantities of Shushufindi, Sacha and Shuara crude oils in an aqueous matrix in culture bottles were inoculated with a bacterial broth obtained from oil-contaminated soil from the Sacha field (see section 2.2.)

Results. GC analyses of the crude oil residues obtained from the biodegradation trials under optimal conditions (Sacha oil, Fig. 25 and Shushufindi oil, Fig. A2 in the appendix) show significant microbial utilization of most hydrocarbons, particularly of the n-alkanes, in the chosen retention time frame of 4 to 18 minutes. Remaining peaks at the end of the experiment indicate resistance to the attack by bacteria and fungi. Metabolic products like esters probably are responsible for the large number of peaks which appear after 24 hours of incubation between 16 and 18 min retention time. From the control it is obvious that volatile components with short retention times like monoaromatics, naphthalene and, to a lesser degree, dodecane, were partially lost by evaporation in the experiment. Through the addition of oxygen, which was applied from a pressurized tank every 12 hours, the volatilization was strongly increased. Due to the loss of the benzenes and naphthalene, which were present in concentrations close to the detection limit, only few data on the biological degradation of these

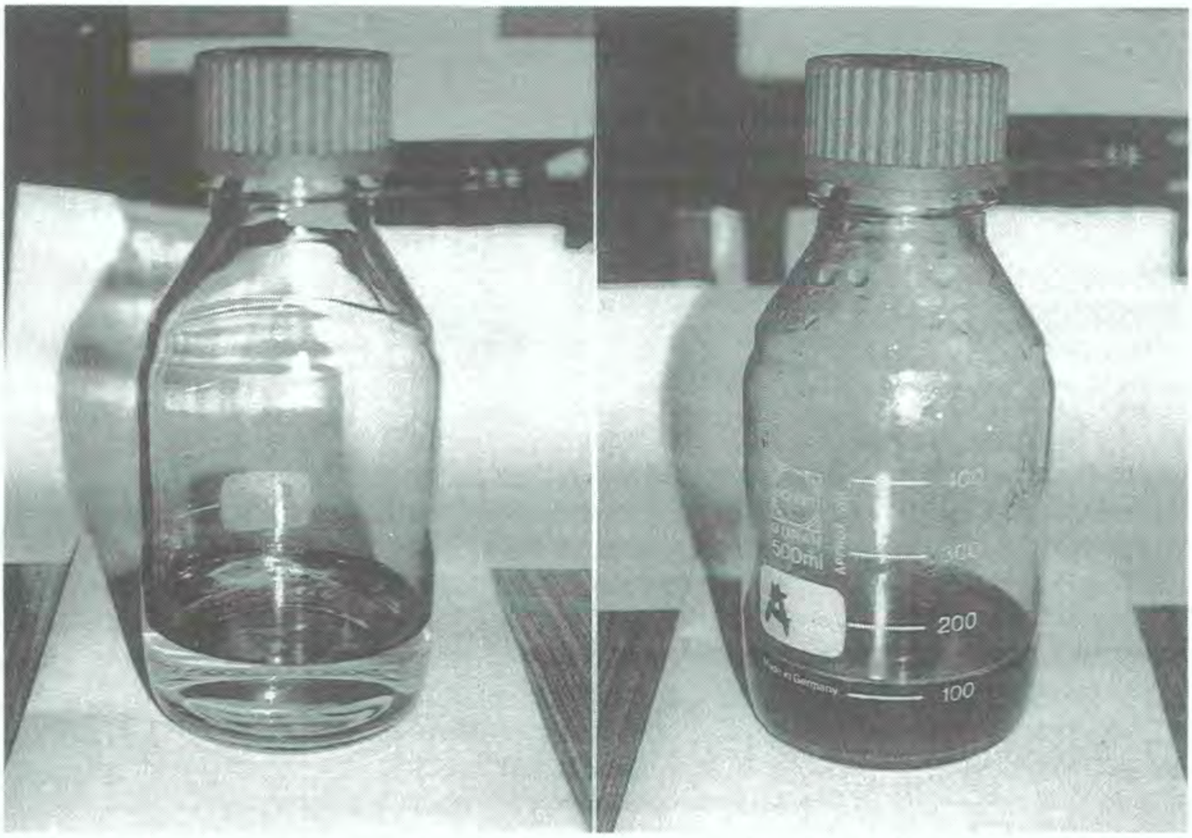

Fig. 24. Culture bottles in the biodegradation experiments (optimum series). Start (left) showing fresh oil floating on nutrient solution. After 24 h of incubation at 30 °C on the shaking table a perfect emulsion has formed (right).

Fig. 24. Frascos con crudo y solución nutritiva en los experimentos de biodegradación (serie de condiciones óptimas). En el inicio del experimento (a la izquierda) se nota el crudo fresco flotando en el superficie de la solución. Después de 24 h de incubación bajo agitación a 30 °C se ha formado una emulsión perfecta entre petróleo y agua (a la derecha).

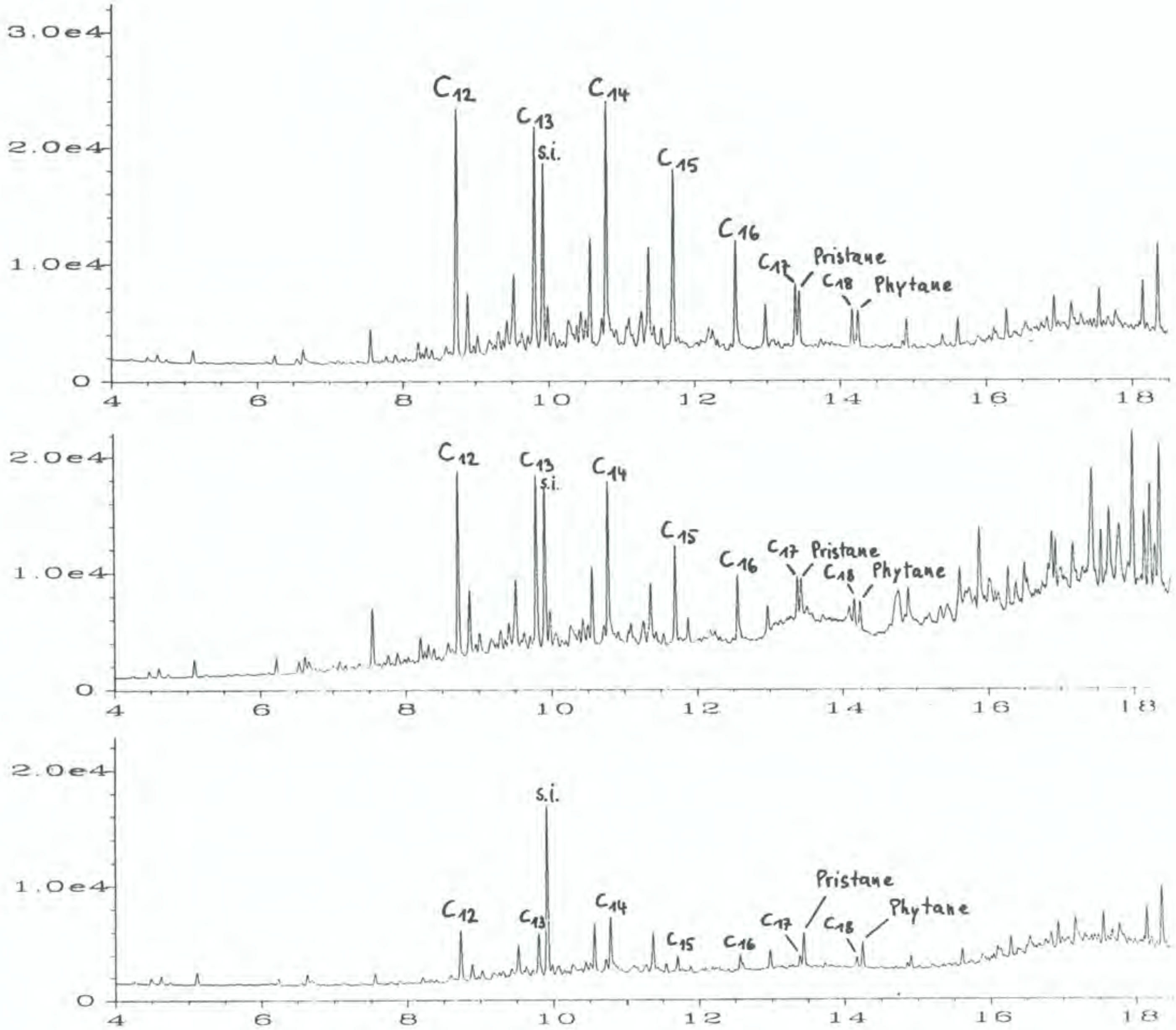

Fig. 18. GC diagrams for Sacha oil biodegradation trials. From top to bottom: control (start), crude oil after 24 hours of incubation, oil after 72 hours of incubation. C_{12}, C_{13}, C_{14} etc. = n-alkanes with number of carbon atoms; s.i. = solvent impurity.

Fig. 18. Cromatogramas de los ensayos de biodegradación para el crudo Sacha. De arriba a abajo: control (inicio), crudo después de 24h de incubación, crudo después de 72h de incubación. C_{12}, C_{13}, C_{14} etc. = n-alkanos con número de átomos de carbon; s.i. = impureza del solvente.

aromatic compounds were obtained.

It was observed that in the culture bottles a perfect oil-in-water emulsion formed within 24 hours which produced foam when shaken. The formation of foam turned out to be a reliable criterion whether biodegradation of oils took place or not. Degradation products obviously act as emulsifiers which facilitate bacterial attack.

Under optimum conditions, for the n-alkanes (dodecane, pentadecane and hexadecane), the highest degradation rate was observed in the first 24 hours of the trial and then slowed down until day 5 when concentrations were extremely low (Fig. 26). The branched alkanes pristane and phytane, however, displayed a rather constant decline in concentration over the 5 days.

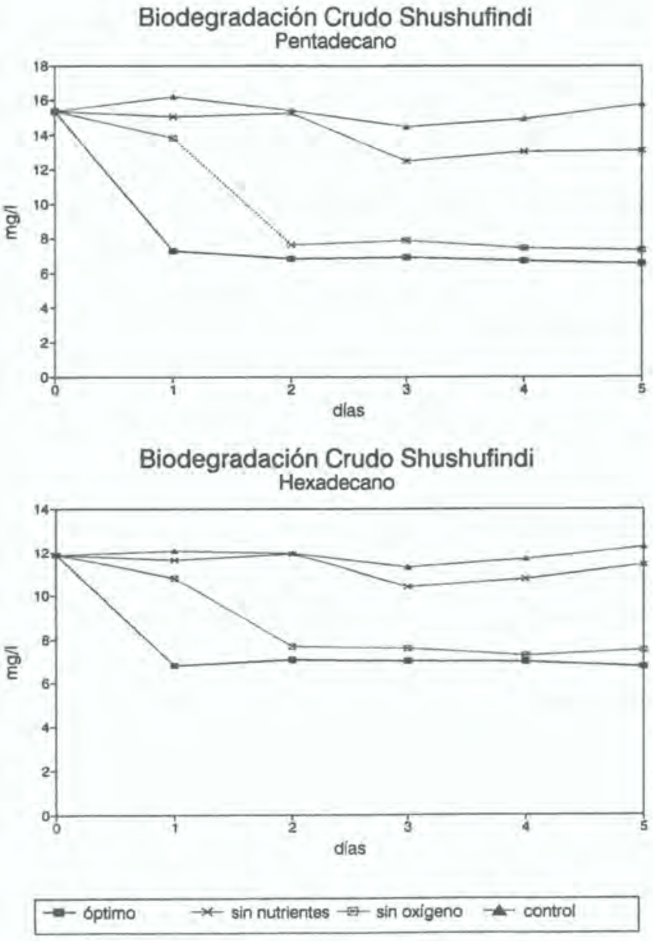

Fig. 26. Biodegradation of pentadecane (C_{15} n-alkane) and hexadecane (C_{16} n-alkane) in Shushufindi oil under different conditions over a 5 day incubation period.

Fig. 26. Biodegradación de pentadecano (alcano C_{15}) y hexadecano (alcano C_{16}) en crudo de Shushufindi bajo diferentes condiciones dentro de un período de 5 días de incubación.

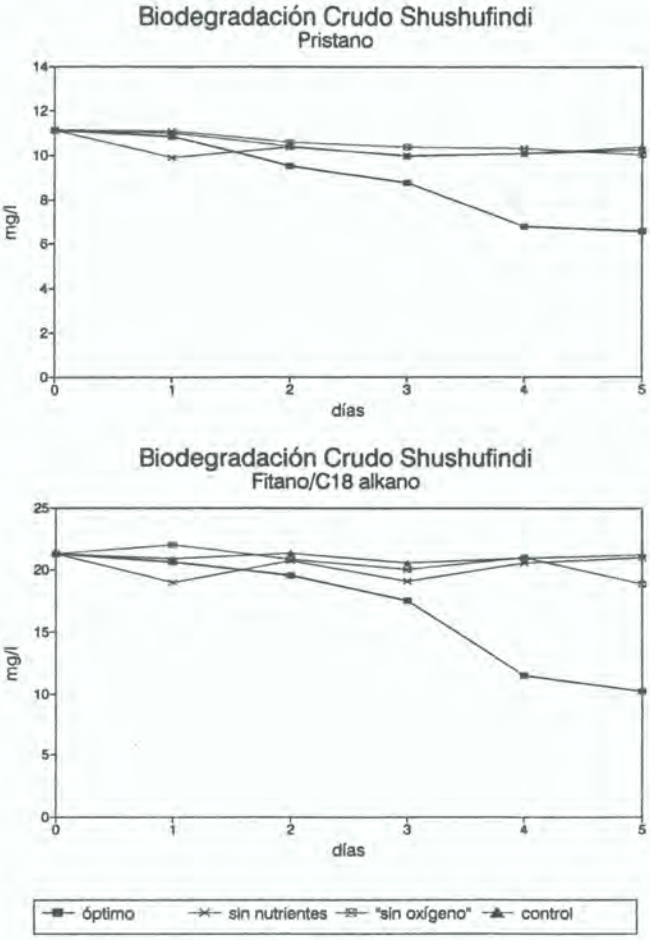

Fig. 27. Biodegradation of pristane (C_{19} branched alkane) and phytane (C_{20} branched alkane) / C_{18} n-alkane (individual peaks not resolved in GC analysis) in Shushufindi oil under different conditions over a 5 day incubation period.

Fig. 27. Biodegradación de pristano (alcano ramificado C_{19}) y fitano (alcano ramificado C_{20}) / alcano C_{18} (picos no resueltos en el análisis cromatográfico) en crudo de Shushufindi bajo diferentes condiciones en un período de 5 días de incubación.

The analyses of the degraded oils show that the biological oxidation is minimal under conditions of oxygen and nutrient limitation (Fig. 27, pristane and phytane/C_{18} alkane, and Fig. A2b,c in the appendix). The values obtained for these experiments are very close to the control, in which all microorganisms were killed with sodium azide solution. The experimental design for the trial series with oxygen deficiency however had a flaw in that the remnant volume of air in the culture bottles was a source of oxygen to the bacteria. Therefore, the "oxygen-free" series showed only a slightly lower degradation of the crude oil as compared with the "optimum" series (Fig. 26, pentadecane and hexadecane). Only in the case of pristane and phytane, which are relatively resistant to

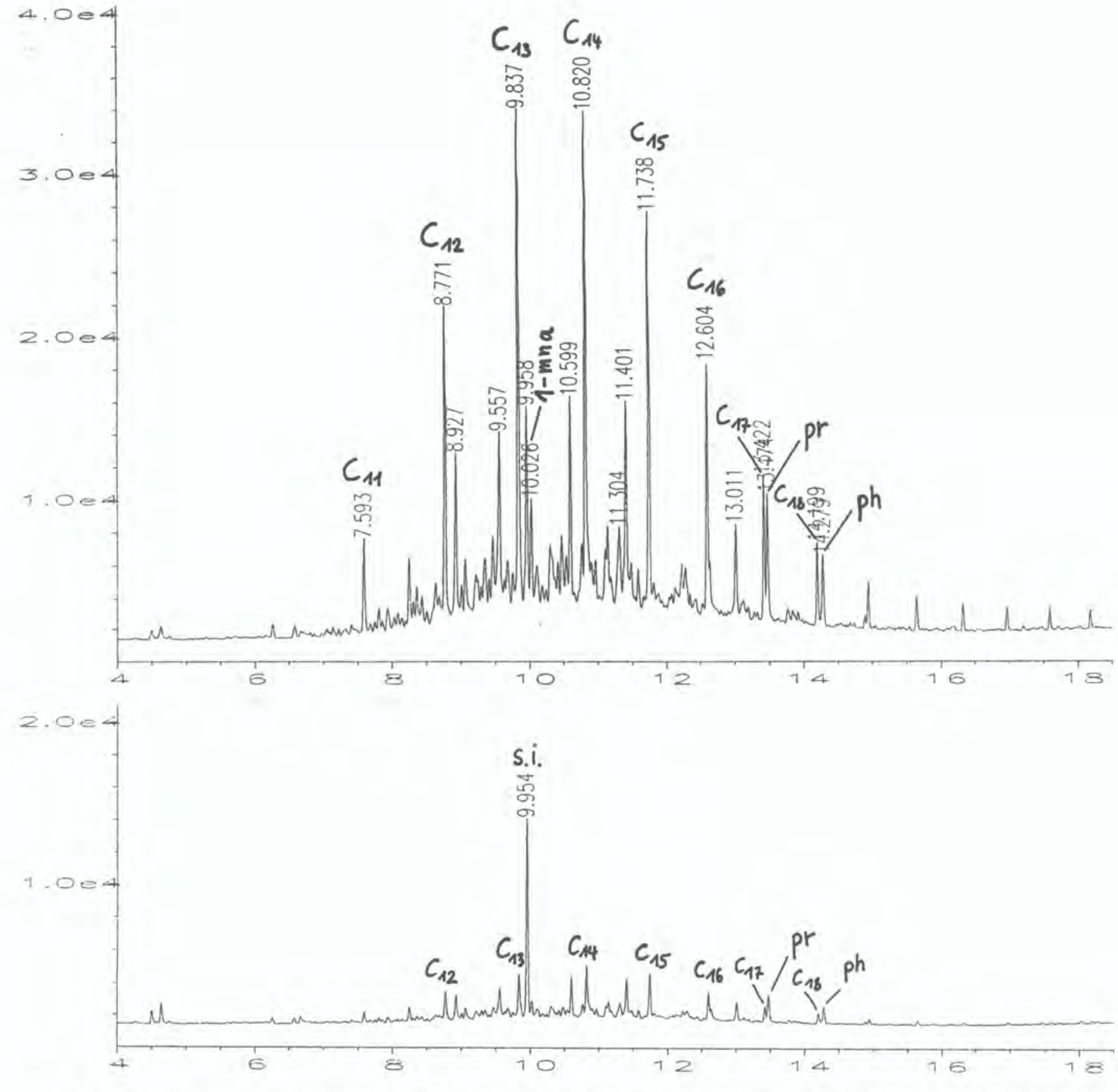

Fig. 28. GC diagrams for soil extracts of Shushufindi oil in biodegradation trials after three weeks at 30 °C. Top: Sample from untreated soil, bottom: sample from fertilized soil. C_{11}, C_{12}, C_{13} etc. = n-alkanes with number of carbon atoms; s.i. = solvent impurity; 1-mna = 1-methylnaphthalene; pr = pristane; ph = phytane.

Fig. 28. Cromatogramas de extractos de suelos de los ensayos de biodegradación para el crudo Shushufindi después de tres semanas a 30 °C. Arriba: Muestra del experimento con suelo no tratado, abajo: muestra del suelo fertilizado. C_{11}, C_{12}, C_{13} etc. = n-alkanos con número de átomos de carbon; s.i. = impureza del solvente; 1-mna = 1-metilnaftaleno; pr = pristano; ph = fitano.

biodegradation, it is obvious that a constant oxygen supply to the microorganisms is necessary for the utilization of these compounds.

Results obtained for the biodegradation trials in natural soils sampled from the Sacha oil field (description of experimental design in section 2.2.) were similar to those obtained for water as culture medium although degradation rates were much slower. Abiotic losses were greater, too. Since the medium-weight crude oils (Sacha and Shushufindi) rapidly penetrated into the soil, and samples were only taken from the surface, homogeneity of the samples turned out to be a problem. It was observed that the Shushufindi oil was degraded more readily than the Sacha crude, similar to the experiments in aqueous medium. The analysis of

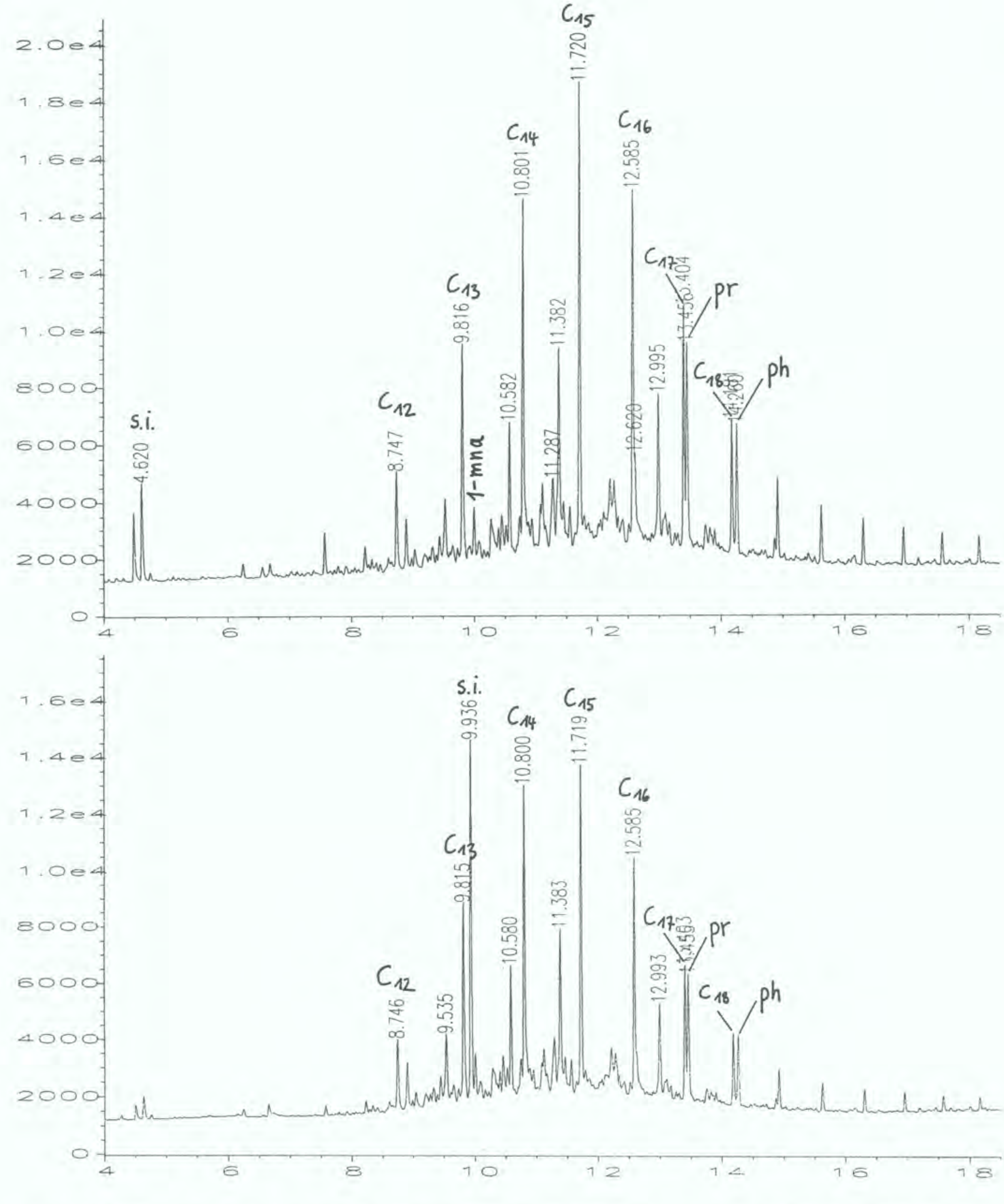

Fig. 29. GC diagrams for Shushufindi oil biodegradation trials in soils after six weeks at 30 °C. Top: Soil sample from experiment in which microorganisms were killed with sodium azide solution at the trial start, bottom: sample from untreated natural soil.

Fig. 29. Cromatogramas de los ensayos de biodegradación en suelos para el crudo Shushufindi después de seis semanas a 30 °C. Arriba: Muestra del experimento con suelo tratado con bactericida para eliminar todos los microorganismos al principio del ensayo, abajo: muestra del suelo natural no tratado.

soil samples taken three weeks after the trial start (Fig. 28) shows that in the series with commercial N-P-K fertilizer added, the removal of hydrocarbons is strongly increased. A comparison of the GC profiles of the control (all microorganisms eliminated) and the untreated soil, sampled after six weeks, shows limited degradation of the crude oil under natural conditions (Fig. 29).

Discussion. The concentrations of all compounds, particularly the n-alkanes, rapidly decrease to a certain level from which further degradation is very slow. This may be explained by substrate limitation (see section 4.2.). Another possible explanation is that toxic metabolic products form which inhibit or eliminate bacterial activity. Since fatty and other carboxylic acids are formed as metabolic products, the pH decreases substantially, which affects bacterial activity. In our experiments, however, this effect was eliminated by adding buffering salts to the culture solution. Analytical problems should also be taken into account since some of the hydrocarbons analysed are present in concentrations close to the detection limit.

The results obtained for the degradation of isoprenoids are similar to results published in the literature. Pristane and phytane occur as distinctive doublets with C_{17} and C_{18} normal alkanes and are much more resistant to biodegradation than the n-alkanes. The GC diagrams (Fig. 25) show that the ratio of pristane to C_{17} alkane and phytane to C_{18} alkane, respectively, changes in a manner typical of degraded oils: from about 0.9 in the fresh oil to 3.0 in the highly biodegraded oil.

Preliminary results in the present study show no detectable microbially mediated losses of the monoaromatics, which are known to exhibit poisonous effects over bacteria. Benzenes, naphthalenes and their substituted equivalents are, to some degree, water-soluble (as are C_{11}-C_{15} n-alkanes) (Kappeler & Wuhrmann 1978). Atlas (1975) concludes from his biodegradation experiments that light crude oils contain toxic volatile components, probably monoaromatics, which apparently are inhibitory to the microbial utilization of oil. Preweathering, i.e. evaporation of part of the volatile fraction of fresh oils, removed this inhibition.

Biodegradation trials of oils in saline formation waters showed that most crude oil components were removed to a similar extent as in freshwaters. It appears that the high content of chloride and trace metals in formation waters does not preclude degradation by microorganisms.

No conclusions can be drawn on the biodegradation of polyaromatic compounds since the method chosen for GC analysis was unable to resolve these compounds to a degree which would permit clear quantification. A separation step in which the polyaromatics are removed from the degraded oil seems to be indispensable.

From the degradation experiments in soils it can be concluded that the limitation of nutrients in tropical soils of the Oriente, which are essential to hydrocarbon-degrading bacteria and fungi, is responsible for a very slow natural oxidation of oils.

Influence of nutrient addition. Roubal and Atlas (1978) found the following order of biodegradation potentials in incubated water samples: naphthalene > hexadecane > pristane > benzanthracene (no nutrient addition) and the order hexadecane > naphthalene >> pristane > benzanthracene (nutrients added). Data obtained by Fedorak & Westlake (1981) indicate that with no added nutrients, the degradation of naphthalene and its methylated derivatives is far more extensive than that of hexadecane (representing a typical n-alkane) after 27 days of incubation. In their experiments, naphthalene was degraded more quickly than hexadecane, which was degraded more quickly than pristane. They also note that nutrient addition increases the extent of microbial degradation particularly of the n-alkanes. Nutrient addition to the inoculated samples stimulated saturate degradation to a greater extent than the biodegradation of the aromatic fraction.

Influence of microbial populations. Fedorak & Westlake (1981) showed that the capability of microorganisms to attack crude oil hydrocarbons depends very much on the availability of a suitable bacteria population. Microorganisms present in sea water samples taken close to an oil refinery were capable of extensive breakdown of saturates and aromatics over the incubation period, whereas the microbial population from a pristine environment left some aromatics and isoprenoid compounds (pristane and phytane) as well as minor saturate hydrocarbons. Fedorak & Westlake (1981) also showed that different microbial populations display a different degradation behaviour, i.e. some populations show preferred utilization of the saturates while others attack the aromatics in the first place. Rowland et al. (1983) observed in laboratory biodegradation experiments virtually no alteration of the simple saturated hydrocarbons until there had been a marked degradation of the aromatic fraction.

Given the fact that the highly weathered tropical soils of the Ecuadorian Amazon are low in nutrients, and oxygen deficiency conditions may develop quickly once the spilled oil penetrates into the fine-grained soil, bacterial degradation of crude oil which has entered the tropical environment may be very limited.

Heavy crude oils, which have an increasing share in the total production from the *Oriente*, consist to a large extent of complex high-molecular weight compounds like asphaltenes and heterocyclic hydrocarbons which are highly persistent in the environment. Atlas (1975) obtained results from biodegradation trials with different crude oils showing that heavy crudes were more resistant to biodegradation. The combination of abiotic losses (volatilization) and biodegradation resulted in removal of up to 80% of the lighter oils but only 50% of the heavier oils over an experimental time interval of 42 days.

Further laboratory experiments are proposed to investigate the microbial degradation of toxic monoaromatic compounds and of heavy crude oil.

6.2.3. Bioremediation Processes

The basic concept in bioremediation of oil-contaminated soils is to stimulate the growth of hydrocarbon-degrading microorganisms. Favourable conditions for the growth of naturally occurring (autochthonous) bacteria and fungi are created mainly by nutrients, oxygen and water supply.

In principle, all petroleum compounds may be attacked and decomposed. In practice, however, even under optimal conditions, a residue of about 20-30% of the initial hydrocarbon concentration, consisting of high molecular weight substances, remains in the polluted soil. Gas chromatography analyses of the residue obtained after a state-of-the-art bioremediation process applied to a industrial site in Germany, contaminated with motor oils, showed mainly branched alkanes with more than 20 carbon atoms to persist (Rippen et al. 1994). The authors of the study found out that these residual compounds were insoluble in water and of almost no ecotoxicological relevance (Rippen et al. 1994). Nevertheless, it should be kept in mind that the determination of the final hydrocarbon residue in microbiologically treated soil depends on the solvent used for extraction - asphaltenes and other heavy-weight compounds are almost insoluble in standard extractants like cyclohexane.

Maxus Ecuador Inc. at their production facility use a process which has been optimized for the local conditions. It was found that the oil concentration in the soil to be treated must not be higher than 2,500 mg of oil per kg of soil (2,500 ppm) to ensure an effective degradation. For treatment in lined pits of 40-50 tons capacity, 1 m^3 of contaminated soil is mixed with 0.25 m^3 of organic compost, 0.25 m^3 of woodchips and a certain amount of sand (if necessary to improve soil structure). Agricultural fertilizer of Nitrogen-Phosphorus-Potassium (N-P-K) 10-30-10 is added and the mixture is kept moist. Standing water should be avoided. Continuous aeration is achieved by tilling of the material in regular periods. The thickness of the soil spread out in the pit should not exceed 20 cm to make sure that all the material is turned upside down when tilled. According to the information provided by *Maxus Ecuador Inc.*, the extractable total hydrocarbon content after 6 months reduces to around 25-50 ppm. The effectiveness of the process also depends on the structure of the soil to be treated. Heavy loamy soils with a high clay content need to be mixed with a light matrix material like woodchips, coffee shells (*cascara de cafê*), rice ash (*ceniza de arroz*) or sand to give the material sufficient porosity and permeability for nutrient and oxygen penetration. Organic materials also offer a good matrix for the growth of microorganisms.

Köllner et al. (1993) tested the factors controlling biodegradation in laboratory trials with soils sampled from sites contaminated with diesel fuel, containing autochthonous microorganisms. Results show that soil concentrations of diesel above 10,000 ppm (1%) had a toxic effect on the microorganisms. They observed that the degradation rate slowed down significantly when the remaining oil content was below 1,000 ppm; 100 ppm was the lowest concentration achieved at the end of their experiments. Köllner et al. (1993) explain this value with substrate limitation for the microorganisms and the fact that the remaining hydrocarbons are probably resistant to bacterial attack. The use of detergents (emulsifiers) had no effect on biodegradation. Nitrogen and phosphorus were determined to be the most important nutrients which accelerate biodegradation. Water was identified as an important transport medium for nutrients and oxygen. The degradation was very low both in dry and waterlogged soils.

Best results were obtained with intermediate water content (moist soil). A temperature of 30 °C as compared to 22 °C significantly increased the degradation rate. Aeration had the strongest positive impact on biodegradation.

Köllner et al. (1993) also tested the influence of added biomass (bacterial cultures) on hydrocarbon utilization in contaminated soils. They discovered that the mixed population of microorganisms (starter culture) with which they supplemented the soils did have a positive effect on degradation rates, depending positively on the quantity of biomass added. It was observed, however, that the degradation rates in trials with biomass added (allochthonous microorganisms) and no biomass added, converged after a certain time. The authors explain this with the increasingly dominant influence of the autochthonous microorganisms, that is, those which had been present in the soil before the starter culture was added. Köllner et al. (1993) conclude that the inoculation with a culture of non-indigenous bacteria does have a minor effect on biodegradation in soils compared with the more important factors, which are oxygen supply (aeration), hydrocarbon concentration, nutrient supply and optimal soil moisture (water content).

In the present study, biodegradation experiments were undertaken exclusively with native microorganisms from oil-contaminated soils from the Oriente. Results show that the autochthonous bacteria have a high biodegrading capacity for most hydrocarbon components. It appears that monoaromatic compounds, which are particularly critical from an environmental point of view, are not significantly degraded by the microorganisms.

We may conclude that the use of allochthonous (exotic) bacterial cultures in bioremediation measures in the Oriente will not show better results than the degradation by native microorganisms which already are present in sufficient concentrations at oil-polluted sites. Non-indigenous bacteria, not adapted to the existing environmental conditions in the Oriente, will rapidly die off without harming the local environment, and the native species will take over. The use of imported microorganisms may only be justified should they possess a proven capacity to degrade monoaromatics. In cases where bioremediation work is necessary in an environment with a very low natural hydrocarbon-utilizing bacterial population, e.g. when an oil spill has happened in a pristine location without earlier oil contamination, the affected site could be inoculated with small quantities of contaminated soil from an older spill site.

6.2.4. Oil Spills

Case histories. The impact of crude oil spills on the local environment is discussed in this section using some well documented cases.

In April 1995, a spill of some 1,000 barrels of crude oil occurred at well No. 17 of the Lago Agrio field, operated by *Petroproducción*. The spill was caused by a pipeline rupture which was the result of strong vibrations at the junction of two crude oil pipes. The broken pipe was later replaced without resolving the vibration problem. After the spill, contingency and clean-up measures were performed immediately, using floating buoys, skimmer pumps, etc.. When the site was visited by the study team 8 months later, remnant oil was still found floating in a swampy depression next to the well. Several hundred metres downstream, the creek draining the wellsite was still visibly contaminated and a thin hydrocarbon film formed on the surface of the streamwater when bank sediments were stirred up. Even in the Río Teteye, several kilometres downstream from the spill location, traces of hydrocarbon films were observed floating downstream. It is known that the remaining oil fraction after extensive biodegradation consists mainly of asphaltic and heterocyclic compounds which have a specific weight >1 g/cm^3, i.e. particles which sink to the bottom of a waterbody. The fact that hydrocarbons of specific weight <1 are still to be found after several months of natural degradation points to the resistance of certain light hydrocarbons to biodegradation which may be explained by their toxicity. Further research is needed on this issue.

In October 1995, a small spill occurred due to missing coordination of maintenance work next to the Lago Agrio Norte production facility, operated by *Petroproducción*. An engineering firm hired as subcontractor was replacing a pipeline section in which oil was still flowing when the pipe was cut. From the spill site, the crude oil flowed into a small adjacent creek and polluted a swamp. The contamination became worse when, in a clean-up effort, the oil-saturated soil from the spill site was flushed with a strong water jet into the same creek. The property owner, a cattle-farming colonist, complained about not having

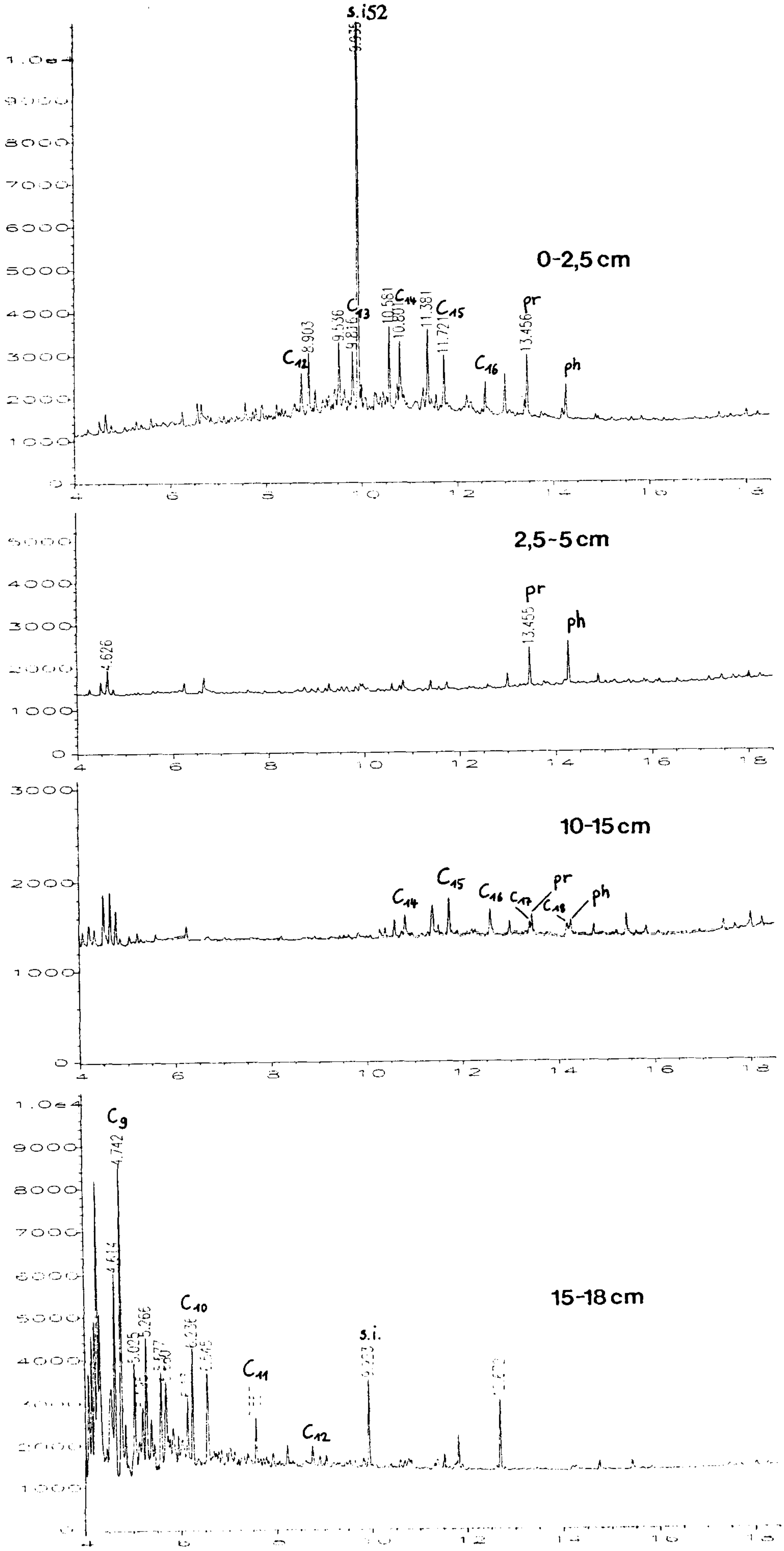

Fig. 30. GC analyses of soil extracts sampled from the bottom of the old production pit at well Aguarico No. 03.

Fig. 30. Análisis por cromatografía de gases (CG) de extractos de diferentes secciones del suelo mostrado en Fig. 30 (fondo de la piscina de producción antigua en el pozo Aguarico No. 03).

received any compensation for the considerable damage to his land. The responsibility for indemnification of property owners affected by oil spills rests with *Petroproducción*, although it seems that in many cases, no or very little compensation is paid.

Oil which was spilled in *Petroproducción*'s CPF Auca Central in April 1995 flowed into the Río Rumiyacu which is a tributary to the Río Tiputini. The contingency plan failed *and Petroecuador* staff set the spilled oil on fire in order to avoid the crude to reach the Yasuni National Park. *Maxus Ecuador Inc.* observed the oil floating on the Río Tiputini at the Yasuni Research Station and calculated that the oil had travelled for 32 hours until it passed the station. There was low water in the rivers. The slow movement of the oil slick downstream presumably allowed for solubilization of water-soluble toxic oil components and extended the duration of strong impact on the aquatic community, like coating and clogging of the respiratory organs of aquatic organisms and causing oxygen deficiency in the water column. Parts of the slowly floating slick also deposited on the river banks from where it was washed downstream at higher river stages. Setting floating oil on fire is a particularly bad practice because mainly the volatile fraction in the surface layer of the oil slick burns (which also evaporates easily) while sufficient oil remains to develop its deleterious effect on aquatic life, aggravated by an acute oxygen deficiency and high temperature in the water column. The fire damage to riverbank vegetation, insects and other animals is substantial.

Most of the oil spills in the Oriente, particularly in the older facilities operated by the former *Texpet* consortium, are due to fatigue and corrosion of the secondary pipelines, i.e. those which connect wells with the production facilities. According to industry information, the most vulnerable and risky parts of the production facilities are locations where a large number of open, secondary pipelines join, close to the CPF's. Within the CPF's, spills occur when separation or storage tanks overflow due to insufficient control and management or when valves do not operate correctly (San Carlos spill).

The largest part of the existing oil infrastructure has been built in the decade between 1970 and 1980. Since all of the pipelines were laid above ground, they are vulnerable to road accidents, falling trees and damage by construction works. Due to the lack of security valves, once a leakage occurs, the flow of oil can only be stopped by shutting the valves at the wellsite. This means that, as a minimum, the total volume of oil in the affected pipeline section will be spilled into the environment. Another problem is the poor

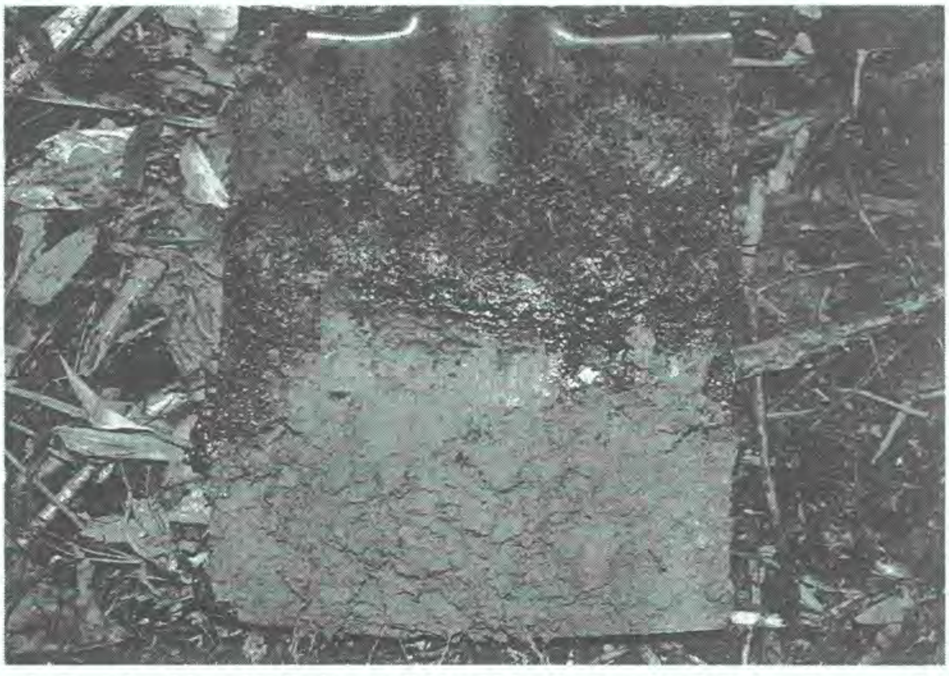

Fig. 31. Soil sample from the old crude oil pit at well No. 03 in the Aguarico field (map in appendix A1). The layer with organic debris above dense clay is saturated with bituminous oil.

Fig. 31. Muestra de suelo del pozo de producción antiguo No. 03 en el campo Aguarico (mapa en anexo A1). La capa húmica por arriba de la arcilla densa está saturado de crudo.

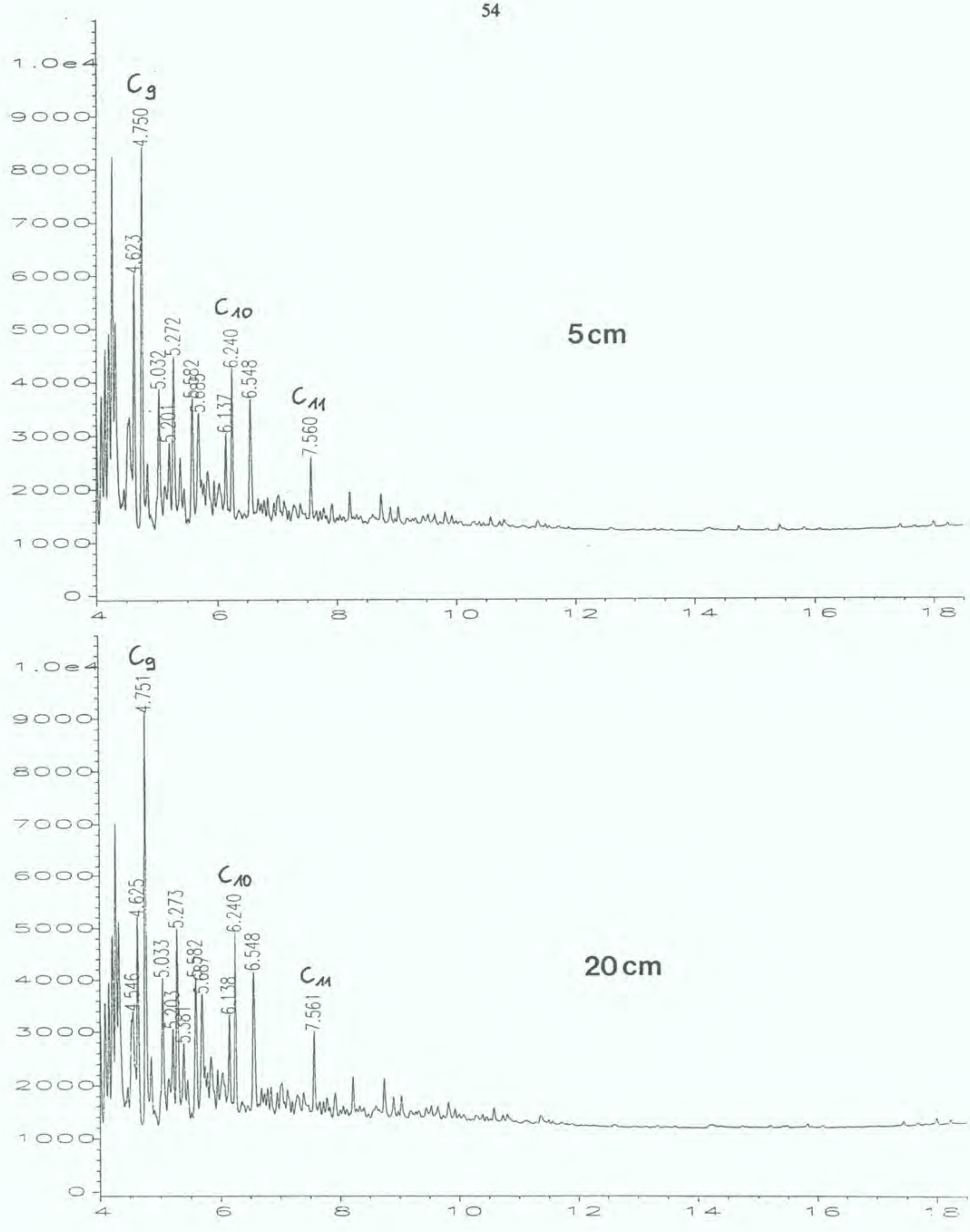

Fig. 32. GC analyses of extracts from alluvions sampled at an older spill site drained by a creek close to well Sacha No. 54.

Fig. 32. Análisis por cromatografía de gases (CG) de extractos de aluviones muestrados en la vega de un riachuelo cerca del pozo Sacha No. 54.

Fig. 33. Pipeline rupture close to well No. 01 in the Aguarico field. The oil flowed into the swampy depression in the background from where the major part was recovered.

Fig. 33. Ruptura del oleoducto cerca del pozo No. 01 del campo Aguarico. El petróleo fluyó hacia el pántano en el fondo, de donde la mayor parte fué recuperado.

and often heavily delayed communication between local inhabitants who first notice a spill and responsible oil company personnel. Large volumes of crude may enter the environment and watercourses in particular before spill combat action is taken. Oil spill clean-up is particularly difficult in inundated areas like swamps and lagoons, e.g. in the large bodies of standing water of the Cuyabeno reserve, which are of unique ecological value.

Investigation of oil spill sites. Soil samples were taken from older spill sites (several years old, P2/5.3. and P2/7.3.) and locations of fresh spills (several months, P1/5.3., P1/7.3. and P1/9.3.). At the abandoned production pit at well Aguarico No. 03 (sample P2/5.3., Figs. 30-31), the uppermost 10 cm of the soil profile (organic-rich layer) are saturated with highly weathered, bituminous oil (Fig. 31).

The soil below consists of a dense clay and is not visibly contaminated with oil. The GC profiles of the upper 15 cm show mainly saturated hydrocarbons from C_{12}-alkanes onwards, whereas in the section 15-18 cm compounds of lower molecular weight (short retention times) dominate (Fig. 30). The soil extracts (in cyclohexane) of the upper 15 cm had a dark brown to black colour. The extract from the section 15-18 cm was very light brown. It appears that below the layer of highly viscous and degraded oil close to the surface, volatile and mobile petroleum components are preserved in the soil.

Sample core P2/7.3. (Fig. 32) was taken from an old spill location in the Sacha field close to well No. 54. The soil material (humic layer at 0-10 cm, loamy soil at 20 cm) showed no signs of oil contamination, the extracts however had a slightly dark colouring. The composition of the recovered oil from the samples taken at 5 cm and 20 cm depth is very similar. Hydrocarbons of low molecular weight with retention times up to eight minutes dominate. One would expect in the soil section closer to the surface the concentration of volatile petroleum compounds to be lower. The much higher organic matter content in the humic soil at 5 cm, which is responsible for binding aromatics and lower n-alkanes, may explain the observed composition.

A pipeline leakage had happened one month before sample P1/5.3. close to well Aguarico No. 01 was taken (Fig. 33). All extracts, from sandy to silty soil, had a deep oily colour derived from asphaltic components, in which only some n-alkanes and isoprenoids could be identified (Fig. 34). Pristane and phytane have high concentrations.

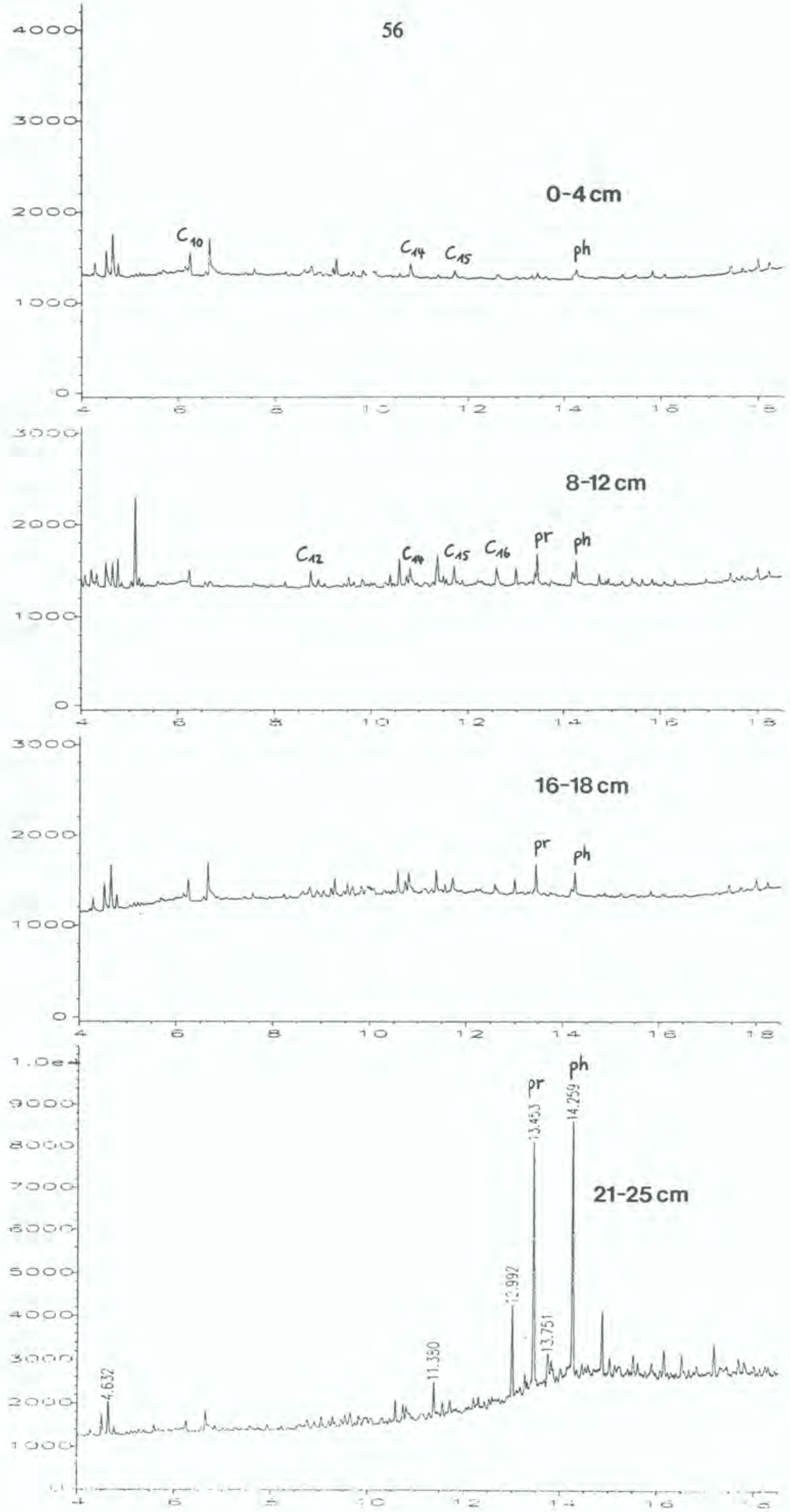

Fig. 34. GC analyses of soil extracts from the fresh spill site close to Aguarico No. 1 shown in Fig. 33.

Fig. 34. Análisis por cromatografía de gases (CG) de extractos del suelo tomado del sitio de derrame reciente cerca del pozo Aguarico No. 01 (Fig. 33).

Extracts from clayey soil at the site of a six months old spill in the Sacha field (sample P1/7.3.) were dark brown (0-5 cm) to light brown (20-25 cm). Both samples are similar (Fig. 35); compounds of low boiling points dominate, particularly in the section 20-25 cm. Sample core P1/9.3. was taken from a recent spill (five months old) in the Lago Agrio field. The GC profile (Fig. 36) of the surface sample (0 cm) shows

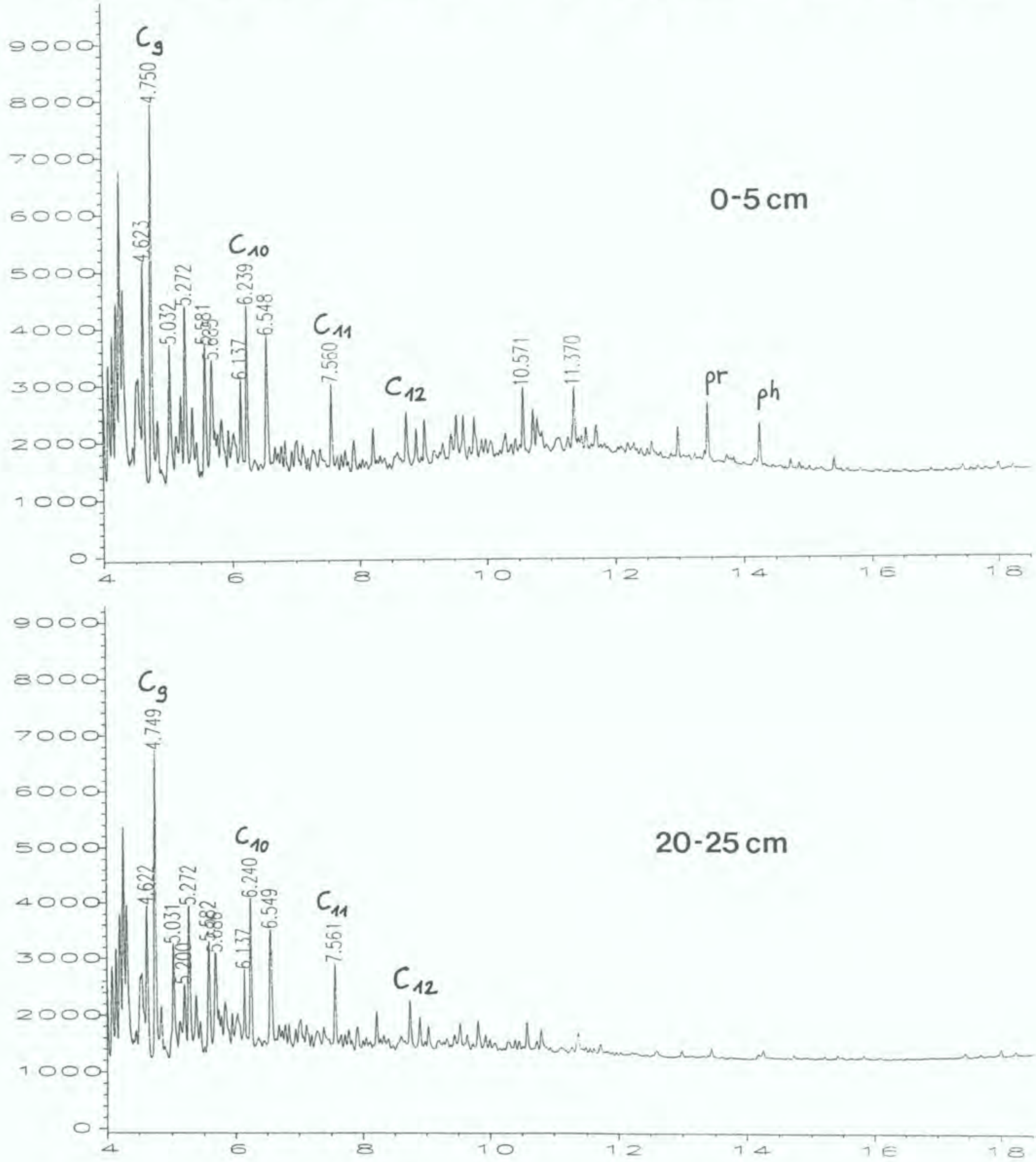

Fig. 35. GC analyses of extracts from soil sampled at a swampy depression drained by a small creek close to the recent spill at well Sacha No. 60.

Fig. 35. Análisis por cromatografía de gases (CG) de extractos de suelo recolectado en un pántano cerca del pozo Sacha No. 60, sitio de un derrame reciente de petróleo.

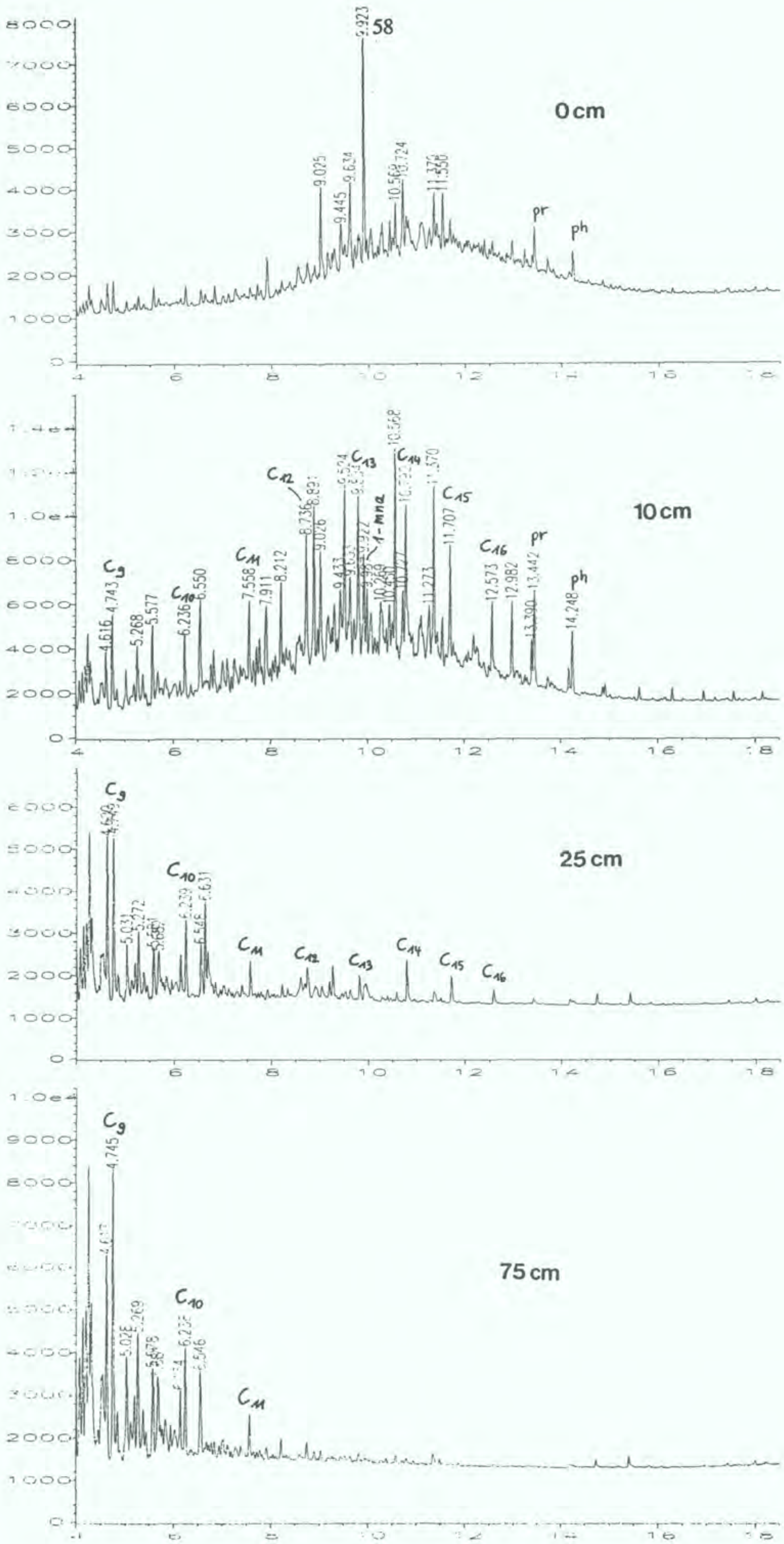

Fig. 36. GC analyses of extracts from soil sampled with a drill corer at a fresh spill site in the Lago Agrio field.

Fig. 36. Análisis por CG de extractos del suelo muestrado de un derrame reciente en el campo Lago Agrio.

the effect of bioremediation measures which were implemented at the site.
The "hump" between 8 and 14 minutes retention time and the envelope of unresolved compounds is mainly formed by metabolic products. At 10 cm depth, crude oil with little signs of alteration was encountered in the silty soil. The slightly brown soil extract at 25 cm depth shows compounds of lower molecular weight, whilst in the nearly colourless sample at 75 cm hydrocarbons with retention times under 8 minutes clearly dominate.

Different physiochemical factors govern the mobility of hydrocarbons in soils, some of which are: adsorption of certain hydrocarbons to organic soil particles in the humic surface layer which prevents them from moving downwards in the soil profile; washing downwards of water-soluble compounds like benzenes and naphthalenes and their substituted equivalents, and C_{11}-C_{15} n-alkanes; emulsification of oil components by microbially formed emulsifiers which could explain the high mobility of some hydrocarbons. The soil properties in terms of porosity and permeability also play an important role in the mobility of oil components and their penetration depth.

The GC analyses of contaminated soils in the present study clearly show a fractionation of the different oil compounds during the downward migration in the soil profile. Hydrocarbons of short retention times, mainly n-alkanes of up to 11 carbon atoms and monoaromatics like benzene and its substituted equivalents like isopropylbenzene, are consistently found at much greater depth than the other crude oil components. This mobile and water-soluble fraction is able to migrate through very fine-grained soils of low porosity and may finally reach the groundwater level.

To summarize, once a spill occurs, volatile components evaporate, the mobile fraction penetrates into the soil or is washed out via surface run-off, and a varying proportion of oil is metabolized by microorganisms. Finally a bituminous surface layer may form (depending on the quantity of spilled oil) which seals off the fresh crude oil below it and prevents aerobic microbial degradation. Nutrient availability (nitrogen, phosphorus) to the microorganisms in the highly weathered soils of the Oriente generally is very low. When fresh crude oil has penetrated into the soil, its water-soluble fraction slowly moves deeper in the soil profile and may persist for decades because of severe oxygen and nutrient limitation to oil-degrading microbes.

6.3. Discussion of Ecological Impacts and Applicable Environmental Guidelines

By presidential decree of August 1995, the Government of Ecuador has adopted new environmental guidelines for the hydrocarbon sector (*Reglamento Ambiental para las Operaciones Hidrocarburíferas en el Ecuador*). Of particular interest to the present study are the maximum permissible limits for liquid discharges and formation waters (*Limites permisibles de Descargas de Fluidos y Aguas de Formación*) which are shown in Table 12. The adopted criteria are similar to the stringent limits of U.S. federal state laws for the petroleum industry. Some important effluent values established as the "Louisiana Criteria", with which some of the new international operations in the Oriente region comply, are: $Cl^- < 500$ mg/L, suspended solids < 50 mg/L, oil and grease < 15 mg/L.

Ecuador has adopted a maximum permissible chloride content in waste water discharges of 2,500 mg/L, although there exist no scientific studies on the environmental impact of high salinity water discharges on the aquatic community of the Oriente rivers. Natural stream and river waters of the Oriente region are characterized by a very low solute content with conductivity values (a criterion for the dissolved salt content) below 150 μS/cm, and in some streams as low as 20 μS/cm. Chloride concentrations in waters unaffected by waste water discharges as determined in the present study were in the range of a few milligrams per litre.

Aquatic organisms like algae, invertebrates and freshwater fish of the region are adapted to these natural environmental conditions. Formation water discharges with a chloride content of 2,500 mg/L into the local streams can clearly have a drastic impact on the freshwater aquatic community. The salinity gradient created in the local brooks and small rivers operates as a chemical barrier, preventing the normal migration of fish and other aquatic organisms between upstream and downstream waters which in turn affects reproductive patterns and species distribution. At least the sensitive species do not survive under the high salinity conditions created by formation water discharges. AMOCO, which has petroleum operations in environmentally sensitive marshland areas in Louisiana, reports that the natural chloride content in local streams may be even higher than 500 mg/L (oral comm., Bob Romero, AMOCO). Considering the local background values in Louisiana, the applicable limit of 500 mg/L chloride probably is sufficient to protect aquatic life. However, in the case of the waters of the Oriente with extremely low natural chloride concentrations, the adopted criterion of 2500 mg/L is certainly unsuitable to protect the aquatic ecosystem and it should be considered to reduce the permissible limit to 250 mg/L or 500 mg/L as a maximum.

Most trace metals of environmental concern are present in the formation waters in relatively low concentrations (Table 6), and after discharge into local waters will rapidly become diluted to values which are not harmful to aquatic organisms. This observation does not hold true for selenium, which is a strong toxicant to aquatic invertebrates and fish. It is methylated biologically in sediments which strongly increases its toxicity. Selenium accumulates in the tissues of aquatic organisms (CCREM 1987). Current environmental regulations of Ecuador have established no permissible limit for selenium.

EXPLORACION, EXPLOTACION, TRANSPORTE Y ALMACENAMIENTO

PARAMETROS	EXPRESADOS EN	UNIDAD	MAXIMO VALOR PERMITIDO
PH	PH	-	5-9
* Temperatura	° C	°C	-
Material Flotante	-	-	Ausencia
Hidrocarburos grasas	-	mg/l	< 15
Sólidos Totales disueltos	STS	mg/l	< 2.500
Cloruros	CL	mg/l	< 2.500
Sulfatos	Sulfatos	mg/l	< 1.200
Sólidos en suspensión	SS	mg/l	Remoción > 80% carga < 40
Sólidos sedimentales	-	mg/l	< 40
** Demanda Química de Oxígeno	DQO	mg/l	< 80
Cadmio	Cd	mg/l	< 0.1
Zinc	Zn	mg/l	< 0.5
Cobre	Cu	mg/l	< 3.0
Cromo	Cr	mg/l	< 0.5
Fenoles	Fenoles	mg/l	< 0.15
Fluoruros	Fluoruros	mg/l	< 5.0
Mercurio	Hg	mg/l	< 0.01
Níquel	Ni	mg/l	< 2.0
Plomo	Pb	mg/l	< 0.5
Vanadio	V	mg/l	< 1.0

Los límites para temperatura serán fijados por el Instituto Ecuatoriano de Obras Sanitarias (IEOS), teniendo en cuenta el caudal del cuerpo receptor, zona de dilución y la temperatura ambiental del área donde va a ser descargado el efluente.

Las muestras serán tomadas del volumen de líquido de descarga.

Table 12. Ecuadorian maximum permissible limits for effluent discharges and formation waters from oil production, approved in August 1995.

Tabla 12. Límites máximos permisibles en la legislación ecuatoriana para efluentes de descargas y aguas de formación en la producción petrolera, aprobado en Agosto de 1995.

A major difficulty encountered in the setting of permissible maximum concentrations of mineral oil and petroleum products is that these are not well-defined chemical categories, but include thousands of organic compounds with varying physical, chemical and toxicological properties (USEPA 1986).

The U.S. criterion for domestic water supply is: "Virtually free from oil and grease, particularly from the tastes and odors that emanate from petroleum products" (USEPA 1986). The recommended maximum concentration for fisheries protection in the European Union is 0.01 mg/L. It has been demonstrated in toxicological studies that concentrations of 0.01 mg/L of crude oil can cause sublethal effects in freshwater fish, and 0.1 mg/L are known to be fatal to sensitive marine larvae (USEPA 1986). In general, plankton (which forms the base of the aquatic food chain) and the eggs and juveniles of aquatic species are particularly sensitive to oil pollution.

Low-energy ecosystems like swamps and floodplains are the most vulnerable habitats where oil can accumulate and persist for a long time. In addition to being toxic, oil can smother burrowing and filter-feeding aquatic organisms, preventing respiration. Oil entrapped in sediments can recontaminate the water column. Below the aerobic surface layer, bacterial degradation of oil in sediments is slow, and the oil can remain unchanged and toxic for long periods, posing a threat to benthic communities.

It has been reported that both wild and domestic animals are attracted by the salt-rich waters in small creeks close to production facilities. Ingestion of toxic constituents like trace metals and hydrocarbons may have severe effects on the animals' health.

6.4. Deforestation in the Oriente

6.4.1. Deforestation related to Petroleum Production

Prior to the start of petroleum production in the sparsely populated rainforest region of Eastern Ecuador in the early 1970s, there existed very little infrastructure, no townships and no permanent roads in the area. This changed rapidly with the coming on stream of the first oil fields in the Lago Agrio, Sacha and Shushufindi areas.

The infrastructure requirements to fully develop an oil field with conventional methods are substantial (Fig. 37). The most important components of petroleum infrastructure are presented below.

Wells and platforms. In older operations, 3-5 ha were cleared for a well site, however an additional 15 ha of rainforest were exploited for lumber which was needed for the construction of drilling platforms and heliports. Modern techniques, however, substantially minimize the area to be cleared. For example, in Block No. 15 (*Occidental*), which is developed by 7 drilling platforms with cluster drilling, one drill pad occupies about 2 ha, with 0.5 ha for each additional well. Cluster drilling means that several wells are drilled from one platform through multi-directional drilling.

Pipelines and oil field service roads. Secondary pipelines which connect individual wells with the central production facilities run along service roads which require a clearing of about 20 m width, i.e. 2 ha/km of pipeline. In a big oil field with a large number of production wells and a dense network of service roads, deforestation is of the order of thousands of hectars (Fig. 37).

Production facilities (CPFs). The central processing installations, together with housing, catering and leisure facilities require large clearings in the rain forest. The central facilities in Block No. 15 at Limoncocha occupy about 40 ha. *Maxus* has built in Block No. 16 a northern and a southern production facility which occupy some 24 ha each. In the older fields developed by the *Texaco-Petroecuador* consortium, both the number of CPFs and their size in each oil field is larger.

Roads. In the last 25 years, oil companies have built a network of roads into the rain forest in order to lay pipelines and to service producing fields. Depending on the vicinity to major established settlements and the date of construction of the road, typcially two to twelve kilometres into the forest along both sides of the road are colonized, meaning that each kilometre of road built results in the deforestation of between 400 and 2400 ha of rain forest.

The U.S. Agency for International Development estimates that more than 500 km of permanent, regional roads built by the oil industry have resulted in the colonization of some 1 mio. ha of rain forest in the Oriente (USAID 1989). Abandoned colonized land and secondary forests are now increasingly being taken over by national agroindustry investors and

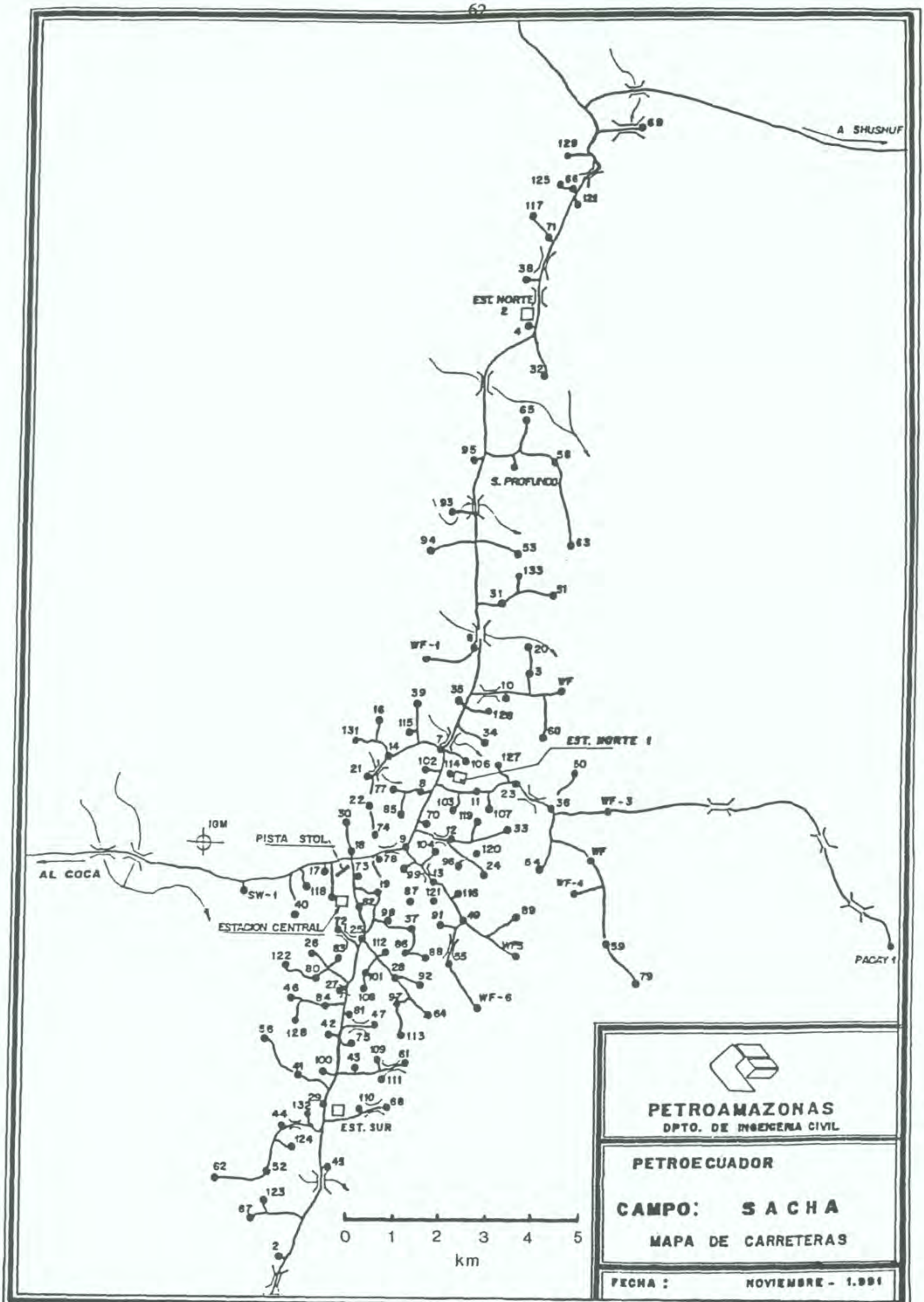

Fig. 25. Road network and production wells (with numbers) in the Sacha oil field, the second biggest in the Oriente.

Fig. 25. Mapa del campo petrolero Sacha, el segundo más grande en el Oriente, mostrando caminos de trabajo y pozos de producción (con números).

converted into extensive palm oil plantations (*Palma africana*) and beef cattle ranches.
Even small seismic paths, of which more than 1000 km are needed for the exploration of a 200,000 ha block, may develop into important pathways for local inhabitants.

In a modern operation, the corridor needed for a dirt road, pipelines, fuel supply and power lines etc., is about 25 m, which means about 2.5 hectars to be cleared for one kilometre of road.

Road construction in the hilly Oriente frequently requires the tops and sides of hills to be shaved off to decrease the slope of exposed lands, hence widening the cleared right-of-way significantly. In places where the roads cross waterways in the rain forest, they act like dams, creating swamps in which the flooded forest dies off and watercourses downstream of the road dam are dried up.

Tree trunks or planks of wood harvested from the adjacent forest have frequently been used as the road base which significantly increases deforestation. *Maxus* calculated that 1.5 km of rainforest on either side of the road which they built in the Yasuni National Park would have to be exploited for big trees to provide sufficient lumber for the construction of a wooden road base (oral comm., Milton Ortega, *Maxus Inc.*). In *Maxus'* and other new developments, synthetic fabrics ("geogrid", "geotextile") replace wood as the base material. Still, about 3,000 m^3 of sand and gravel, mined from rivers and pits nearby, for each kilometre of the road are needed.
In the case of the operation of *Occidental* in Block No. 15, it was decided not to build a bridge crossing the Río Napo to connect production sites because this would facilitate the inflow of colonists and increase deforestation. The crude oil pipeline passes below the river bed.

It should be emphasized that the permanent road network connecting the Amazon lowland with the rest of the country not only opened access to the invasion of colonists, but forms an important export corridor for agricultural products and tropical timbers (Fig. 38). The exploitation of logs and its transport with heavy trucks could only begin once the transandean road parallelling the pipeline was completed.

6.4.2. Estimates of Deforestation Rates

The area of the five Oriente provinces (Sucumbios, Napo, Pastaza, Morona Santiago and Zamora Chinchipe) is approximately 13 mio. ha. For the area of

Fig. 38. Heavy trucks loaded with logs on the road Lago Agrio - Quito which runs parallel to the transandean oil pipeline.

Fig. 38. Camiones cargados de madera en rollo en la carretera Lago Agrio - Quito que corre paralelo al oleoducto transecuatoriano.

Zamora Chinchipe no figures are available because it is located in the zone of border dispute with Peru.

Province	**Area in ha**
Sucumbios	1,815,000
Napo	3,528,000
Pastaza	2,952,000
Morona Santiago	2,914,000
Zamora Chinchipe	1,500,000 (estimated)

The area with original humid tropical rainforest cover was about 90%. In a 1987 study, the *Instituto Nacional de Colonización de la Región Amazónica Ecuatoriana* identified 5,380,000 ha of tropical forest in the four provinces (without Zamora Chinchipe) listed above as "colonization fronts". A comparison of the situation in 1977 and 1985 (based mainly on satellite images) produced the result that the forest cover in the investigated area had diminished from 84.8% in 1977 to 74.1% in 1985, which corresponds to a loss of 575,653 ha in eight years or 72,000 ha/year. This estimate of forest destruction, attributable to a large part to the infrastructure created for petroleum exploitation and subsequent colonization, appears very conservative.

Conservationists (Romero 1989) assume a forest destruction rate, including national parks and biological reserves, of up to 350,000 ha/year in the Oriente, leaving in the year 2,000 only 15% of the original rainforest cover. Cornejo (1995) calculates that more than one million hectars have been occupied by colonists in the period from 1972 to 1994. In a study conducted by Fundación Natura (1994), official figures are quoted stating that between 1972 and 1985, the total deforestation in the Oriente was 1,600,000 ha, equivalent to 123,000 ha/year, which appears to be a realistic estimate.

Current oil production activities span a surface area of nearly 1 mio. ha in the Oriente. Although the deforestation directly caused by petroleum activities in a 200,000 ha block varies between 400 and 2,000 ha (less than 1% of the total area), the extensive road network created and the control of use of these roads are the critical issues.

6.4.3. Problems of Rainforest Reforestation

All of the petroleum companies maintain tree nurseries in their operations which are used to replant mainly native tree species on completed drilling sites and clearings made for infrastructure developments like roads and pipelines. At *Petroproducción*'s tree nursery in Lago Agrio, about 170 different plant species are cultivated of which more than 80% are indigenous. According to the nursery's manager, it is becoming increasingly difficult to obtain the seeds from the rainforest on which the tree nursery depends. Several typical local tree species like *cedra*, *caoba* and *balsamo*, which are high quality timbers, have disappeared from the area. Commercial loggers are now harvesting even the poor quality timbers which have been left behind in the first exploitation stage.

The re-establishing of rainforest on a cleared site with disturbed topsoil is very difficult; primary tree species do not tolerate the permanent exposure to sunlight which means that they only can grow in the shade provided by pioneer trees. Since seeds and seedlings of late-successional (primary) tree species are present in a degraded rain forest in very low numbers only, the natural succession is uncomplete.

The artificial revegetation by grasses and other herbaceous species on cleared areas creates a dense floor cover which may prevent the growth of pioneer trees which need much light for their seeds to germinate. Because the regeneration of vegetation on a cleared site is dependent on the transfer of nutrients from the soil to vegetation, soil rehabilitation and the presence of an organic layer are crucial for the succession from grassland to a climax forest. An intact soil is also needed for the colonization with woody species which grow from the seed bank of pioneer trees which is typically buried in the soil (large banks of pioneer species seeds, which can remain dormant for long periods, have been found in tropical forest soils (Reading et al. 1995).

The most rapid natural succession occurs when the undisturbed rainforest can laterally move onto the (small) cleared space to close the gap. Regrowth is best and most rapid when topsoil and root systems are undisturbed, a condition which is given in the revegetation of small clearings or paths cut into the forest, e.g. for seismic exploration. The succession pattern then resembles that of endodynamic forest disturbances like dead tree falls. It should be noted, however, that even the clearances cut for seismic lines, few metres in width, e.g. in former *Texaco* fields, can remain visible by remote sensing for several years when the tree canopy is disturbed (Cornejo 1995).

6.5. Impacts on Local Inhabitants and Wildlife

As mentioned above, the heaviest ecological impact is caused by the infrastructure created for the petroleum exploration and extraction. North of the Río Napo, the rainforest is heavily degraded and depleted in terms of species diversity and population size. It is worthwhile to discuss in some detail the impact which the infrastructure associated with petroleum activity has on a pristine environment, taking as an example the road which had been built by *Maxus Ecuador Inc.* between October 1992 and September 1994 in and around the Yasuni National Park (Fig. 39). It should be stressed that the rainforest in the region is fairly homogenous and nearly untouched by man; hence the differentiation between areas inside and outside the Yasuni Park is only a formal one (the road built by *Maxus* is totally located within the boundaries of the original Yasuni Park as created in 1979).

The following direct environmental impacts of the road are to be expected (assuming no colonization occurs): emissions of dust and noise due to traffic; modification and interruption of local drainage patterns (e.g. drowning of forest trees in newly created bodies of stagnant water); habitat fragmentation and subsequent loss of species which require a large habitat (e.g. most mammals); avoidance behaviour and impediment of animal migration of temporal or permanent character.

Indirect socioecological effects which have been experienced at other project sites are: hunting and trading with rare animal species by construction workers and company employees; the road may act as an incentive for indigenous people to excessively hunt and collect marketable species because transport to the nearby commercial centres is facilitated; change of social patterns of the local inhabitants leading to environmentally destructive behaviour (without considering social consequences such as cultural erosion, alcoholism, violence, prostitution and cultural dependency which, if they occur, are not attributable especifically to the road, but to the project as a whole).
Detailed zoological, ecological, archaeological and anthropological studies were undertaken on behalf of *Maxus Ecuador Inc.* to select the best routing of the road and to minimize adverse environmental impacts. The large workforce needed during the construction works was trained in appropriate social behaviour towards the Waoranis, and a strict vaccination scheme was implemented in order to avoid the spreading of contagious diseases. The road and the pipeline which runs parallel in most sections, required a clearing of some 25 m in width. In sections with steep slopes, where the terrain had to be stabilized with banks, the deforested right-of-way is much more than 25 m. Although the clearings made to bury the pipeline will be revegetated (to a maximum tree height of about 2 m), it is not possible to maintain a closed canopy cover over the road (which has a width of 8 m). The attempts by *Petro-Canada*, which did exploratory work in Block No. 9 south-west of the Yasuni Park, to preserve much of the forest canopy as a bridge for animals over a new road into primary forest, were unsuccessful. Water drainage management and the need that solar radiation reaches the road to dry up its surface are important considerations when building a road in humid tropical forest.

The road network within and outside the Yasuni park, in virgin rainforest, has a total length of about 150 km without considering the clearings made for the pipeline where it does not run parallel to the main road. A total of 800 ha, including 527 ha cleared for seismic paths and 183 ha needed for heliports (Cornejo 1995), has been deforested during block development and construction. An estimated 500 ha of rainforest will be permanently occupied by the project installations with approximately the same area being reforested after completion of the construction period.

The effects of the road on the local environment are being monitored by a consultancy firm, *Ecuambiente*, contracted by *Maxus Ecuador Inc.* which carries out research in collaboration with scientists from abroad. The heaviest impacts were observed during the construction of the road. The generation of dust affects plants and particularly flowering species, on which many insects depend. Assuming that the forest at the edges of the road remains intact, the disturbance of insects appears to be minimal. Most birds have probably got used to the noise emissions. It should be stressed, however, that resident, sedentary species are known to be the most affected by habitat disruption, as opposed to nomadic or migrant species (Coates & Lindgren 1978). Monitoring results obtained so far (oral comm., *Ecuambiente*) indicate that the monkey

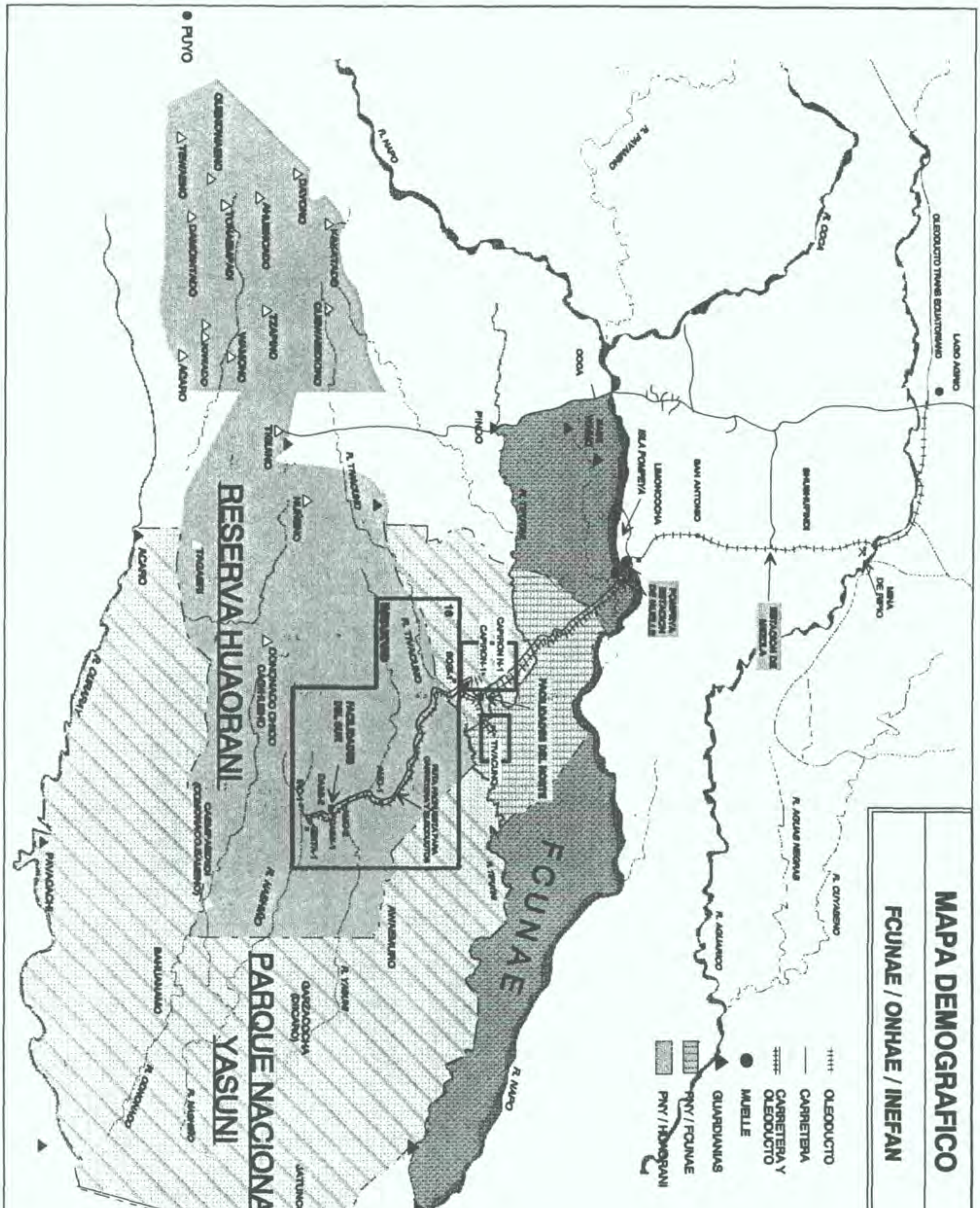

Fig. 39. Map showing some of the major roads in the Oriente and the oil road built by *Maxus* within the Yasuni National Park and the Waorani Ethnic Reserve.

Fig. 39. Mapa mostrando algunos de los mayores carreteras en el Oriente y la carretera construida por *Maxus* dentro del Parque Nacional Yasuni y en la Reserva Etnica Huaorani.

population seems to be affected by habitat fragmentation.

In recent years, tropical scientists have discovered the ecological importance of the rainforest canopy as the habitat for a large range of animals. The effects of a large gap in the canopy on the animal community is difficult to evaluate because routine monitoring usually is restricted to the lower vegetation strata and the forest floor.

Ecologists working at the *Ecuambiente* research station, however, conclude that the road has a population-separating effect comparable to a river in the rainforest.

The *Maxus* road is also an important corridor in the dense jungle which facilitates access for hunting. The Waoranis, which have the ability to smell the scent of e.g. wild pigs over a distance of several hundred metres, make use of the access provided and also of the ease of transport of hunted animals. The increased hunting pressure, together with the use of more efficient weapons (firearms), poses a serious threat to the wildlife in the vicinity of the road.

This phenomenon has been reported elsewhere, for example in the Star Mountains of Papua New Guinea, where a large copper-gold deposit in a pristine rainforest environment with an indigenous population that previously had minimal contact with western civilization, was developed in the 1970s. The populations of bird of paradise species and a now nearly extinct large flying fox (*Bulmer's fruit bat*) were eliminated due to the access provided by mine roads and the availability of shotguns and other modern hunting equipment (oral comm., Tim Flannery, Papua New Guinea Department of Environment and Conservation). Hunting strategies of the Wopkaimin Papuas resident in the Ok Tedi area were rapidly changing.

In their study of the birds of the area, Coates & Lindgren (1978) found out that predation by humans, both local inhabitants and mine employees, provided the greatest threat to the avifauna in the Ok Tedi perimeters while significant habitat destruction as a direct result of the mine construction could be discounted. Similar to what has occurred in other disturbed rainforest regions of Papua New Guinea, Coates & Lindgren (1978) detected that in the project's area of influence, the large prime food species disappeared first, followed by "status species" of decorative value like birds of paradise, parrots, cockatoo and hornbills. The use of firearms was identified by Coates & Lindgren (1978) as the greatest threat to the avifauna which may be considered as an indicator group for other hunted animals.

The road built by *Maxus* in the Yasuni Park also increases the mobility of the Waoranis, their access to markets and their consumption pattern. As a result of the introduction of cash economy, it may also happen that hunters sell their game or living animals for the pet trade, as has been observed in other parts of the Oriente (Kimerling 1991), leading to overhunting and depletion of certain species. The presence of a permanent road may act as an incentive to give up their nomadic behaviour, which happened in a number of road projects in rain forests in West Africa (Wagner 1984).

In the Ok Tedi area, it has been observed that the indigenous population, particularly young people, moved their settlements towards the newly constructed project road. This type of migration has not yet happened at the *Maxus* road, however, it remains to be seen what impacts the road will have on the mobility and associated social patterns of the now rapidly growing Waorani population. The permanent contact with western civilization and the increased cash flow to the Waoranis (part of whom are working in the project) will alter their lifestyle and their use of forest resources. The indigenous Shuaras and Quichuas who are living in areas of petroleum activity north of the Río Napo, have been exposed to those influences for a longer time and today develop agricultural and economical activities similar to that of non-indigenous colonists.

Maxus has designated the task of protecting the Yasuni National Park and the Waorani Ethnic Reserve to the Waoranis themselves which seems to have successfully prevented the intrusion of colonists via the road. A similar phenomenon is observed in the neighbouring Block No. 15, where (according to information provided by *Occidental Ecuador*) colonization is not a major problem because the indigenous inhabitants hold land titles and have violently defended their territory against colonists.

In the case of *Maxus* and the Yasuni Park, the most serious environmental issue, however, is the permanence of the road and its future uses. When the Government of Ecuador gave its approval for the road, an important consideration was that other companies could use *Maxus's* road to exploit concessions deeper in the forest. Although *Maxus Ecuador Inc.* is committed to dismantle the road once its operating contract expires in 2011, this appears unlikely due to political pressures. The Ecuadorian military, which considers nearly the whole Oriente as a sensitive border region and has always been in favour of the establishment of settlements in this vast "uninhabitated" space, will certainly push to maintain the road. This would result in the influx of landless migrants, agricultural colonization along the highway, and conversion of forests to pastures for cattle ranching, all resulting in a rapid degradation of the rainforest comparable to what has happened in the last 25 years, following the first oil discoveries, in the region north of the Río Napo.

In the Cuyabeno Wildlife Reserve, about one third of the total area of 255,000 ha has been colonized along oil roads, destroying forests and displacing indigenous peoples from their traditional lands (Kimerling 1991). The *Maxus* road may also be seen as an important part of the traffic network in the Oriente which in 2011 probably will be much larger than today. Finally, pressure by logging operators who want to exploit a forest of primary qualities and enormous monetary value will be high, considering the depletion of timber resources elsewhere and a sharp rise in tropical timber prices to be expected. Logging is considered to be one of the most important economic alternatives once the oil fields of the Oriente are exhausted.

7. Recommendations

7.1. Technical and Regulatory Recommendations

Based on the analysis of the environmental and social impact of petroleum production in the Oriente, a number of recommendations are made which may help to improve the environmental performance of already producing and planned projects. We distinguish between recommendations directed to the oil industry and their environmental experts, and governmental regulators.

To oil industry and field operators:

- Reduce high concentrations of petroleum in production water discharges, particularly from CPFs of the former *Texaco-Petroecuador* consortium, by improving the oil/water separation process in the installations and by reinjection of purified production waters into the subsoil to reduce waste water discharges in general

- Use exclusively biodegradable chemicals in drilling and processing steps and optimize the quantities employed

- Improve the management plans and prevention measures for accidents and spills in general; critically evaluate and improve contingency plans; conduct case studies in failed attempts to control oil spills; introduce a common industry standard for personnel involved in oil spill clean-up, e.g. a certified training course with periodic refreshening courses

- Apply bioremediation techniques for contaminated soils with emphasis on *in situ*-remediation to minimize soil and habitat disturbance

- Develop a simple, quick and economic preventive monitoring method for the condition of pipework, particularly secondary pipelines (checking pipe wall thickness by ultrasonic, X-rays)

- Improve management system in the CPFs by better coordination and communication of work done on sensitive parts of the installations (e.g. replacement of pipework), particularly with sub-contractors

- Improve communication, share experiences and disseminate information on successes and failures in environmental engineering and management among companies and government agencies involved in the oil industry

- Finally, taking into consideration the limited availability of oil as a non-renewable natural resource and its value to future generations, oil companies should ensure maximum recovery and improved efficiency in their fields under exploitation; the application of secondary and tertiary exploitation methods should be explored

To governmental regulators:

- Develop environmental standards (e.g. for production wastewaters) achievable by state-of-the-art-technology which are comparable to U.S. and European criteria

- Establish a valuation system for damage caused by oil spills to private property, set up norms for compensation

- Require consultation and participation of local people in the selection of drill sites and location of petroleum processing facilities and housing compounds; involve indigenous inhabitants in the protection of parks and reserves (like the Waorani in the case of the Yasuni Park and Ethnic Reserve)

- Create a regulatory framework to require reports on pipeline condition in the oil fields operated by each company in appropriate time intervals

While the pollution of soils, water and air linked to petroleum development is predominantly a problem to the inhabitants of the region, both indigenous and colonists, it is the loss of natural habitats which threatens tropical forest fauna and flora. Crucial to the maintenance of the ecological integrity of the rain forest system is the **"no net loss"** approach. Similar to regulations in the United States, the Ecuadorian authorities should require rain forest creation or restoration as a condition of permitting activities in primary or secondary forests of the Oriente.

Prior to the start of oil development activities, a forest inventory and classification based on satellite images using Geographical Information Systems (GIS) should document the state of the affected rainforest in the 200,000 ha concession block. The rain forest inventory may form the base of a management plan which includes figures on the area needed for petroleum infrastructure, already degraded forests, areas inhabited by indigenous people and colonists, and definition of frontier zones where colonization is advancing. Oil companies should accept responsibility for colonization and deforestation in their oil lease blocks where they are a consequence of infrastructure built for the oil development; the companies should seek solutions to the colonization problem in coordination with the Ecuadorian authorities. Areas in which rain forest is lost should be compensated for by restoration of degraded forests and formerly forested areas. All major oil companies maintain tree nurseries and have the expertise for forest reclamation.
The "no net loss" concept should be made part of the contracts signed between oil companies and the Ecuadorian state.

7.2. An Environmentally Friendly Alternative to Conventional Oil Production - the ARCO Model

An innovative model for oil development in environmentally sensitive areas has been developed by the U.S. company *ARCO International Oil & Gas Company* which its Ecuadorian subsidiary, *ARCO Oriente Inc.* is planning to implement in its operation in Block 10 in the Oriente for which the concession contract was signed in June, 1988. The main goal is to minimize the adverse environmental and sociocultural impact of oil development in a rain forest. A detailed description of the concept is given in the appendix.

ARCO Oriente proposes a concept based on already applied and proven methods to minimize the environmental impact in oil developments, linked with the idea to transfer the offshore oil production design on land. Key features are:

- Minimize the "footprint" of all operations by strictly limiting the affected area (e.g. a maximum of two hectares for drillsites); maximize clearing by hand, thus preserving the topsoil; minimize the use of heavy equipment; operate without roads and replace them by airborne transport (helicopter); restore and reforest disturbed sites

- Limit the rights of way for "wet" oil pipelines to 6 m (20 ft.), construct no paralleling road, maintain the tree canopy over pipelines; use a high pressure resistant, flexible fiberglass pipe instead of conventional steel tubes; lay pipelines by hand on the surface, bypassing major trees

- Keep on-site equipment complexicity as low as possible, maximize reliability and durability of the installations, employ closed systems to avoid pollution (no pits)

- Monitor for leaks, accidents and other operational problems at the field and along the pipeline with electronic detection and communication devices

- Consult and communicate with local communities during all development stages, e.g. by letting the indigenous people select the trees for lumber harvesting and drillsite location

- Build no permanent on-site camps for workers, thus diminishing interference with local people and avoiding the total submergence of indigenous culture to the intruding culture

- Implement remote field operation, locating production processing centre and worker housing at the nearest community in a populated area along the oil pipeline route

The company claims that its offshore concept is less expensive than a conventional operation. Construction and maintenance of a road is costly, as well as the maintenance of a permanent on-site workforce working rotating shifts. *ARCO Oriente* estimates the capital costs to be about 30% and operating costs to be 10% lower than in a conventional operation. The logistics costs can be minimized by reducing in-field equipment weight and by using existing road infrastructure.

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APPENDICES 1-3

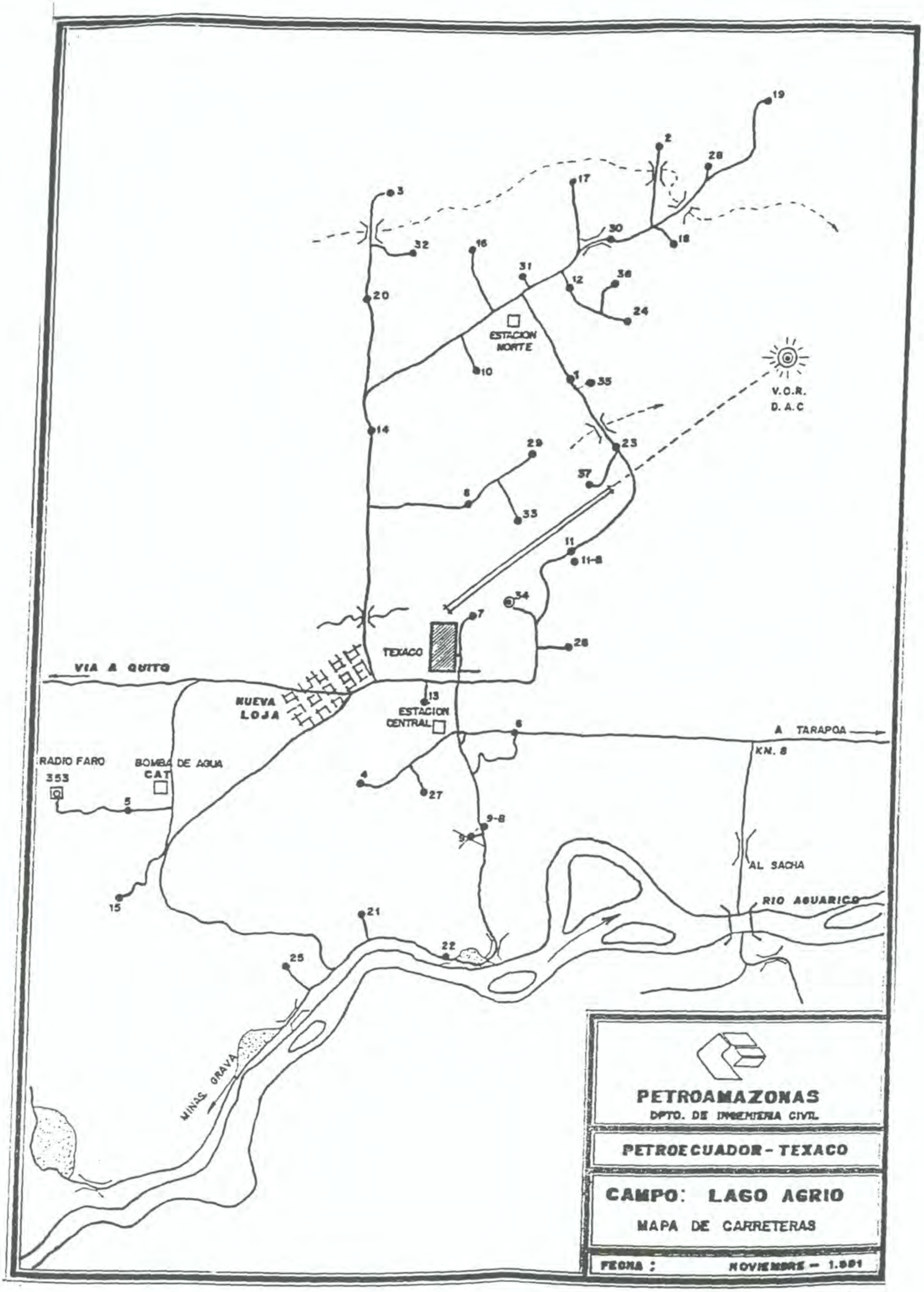
(A1) Maps of major Petroecuador oil fields in the Oriente:
Lago Agrio, Libertador, Aguarico, Shushufindi and Auca

(A2, a-d) Gas chromatograms of Shushufindi crude oil after laboratory biodegradation

(A3) Engineering for Development in Environmentally Sensitive Areas -
Oil Operations in a Rain Forest

by

ARCO and ARCO International Oil and Gas Company, U.S.A.

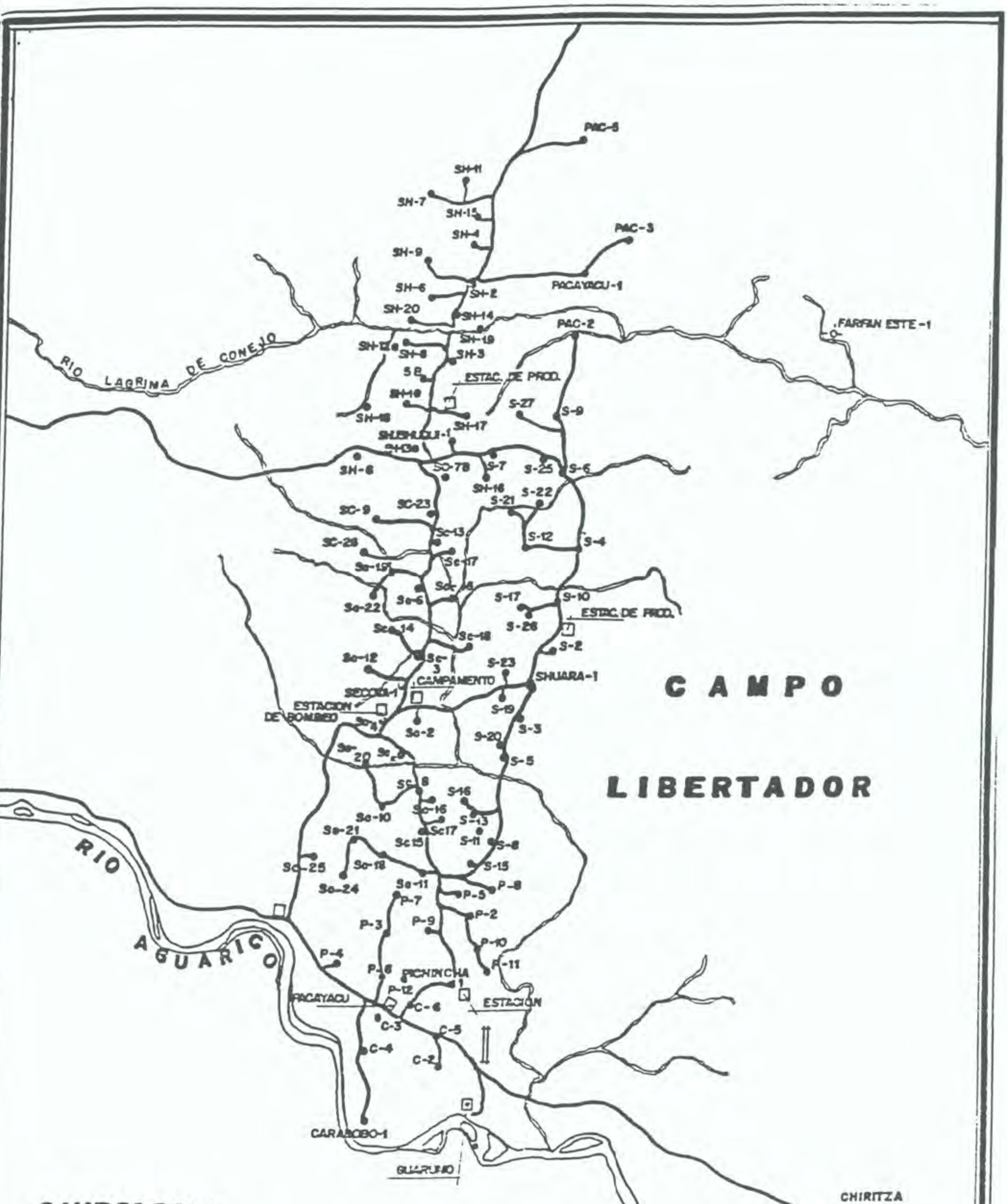


PETROAMAZONAS
DPTO. DE INGENIERIA CIVIL

PETROECUADOR - TEXACO

CAMPO: LAGO AGRIO
MAPA DE CARRETERAS

FECHA : NOVIEMBRE - 1.991



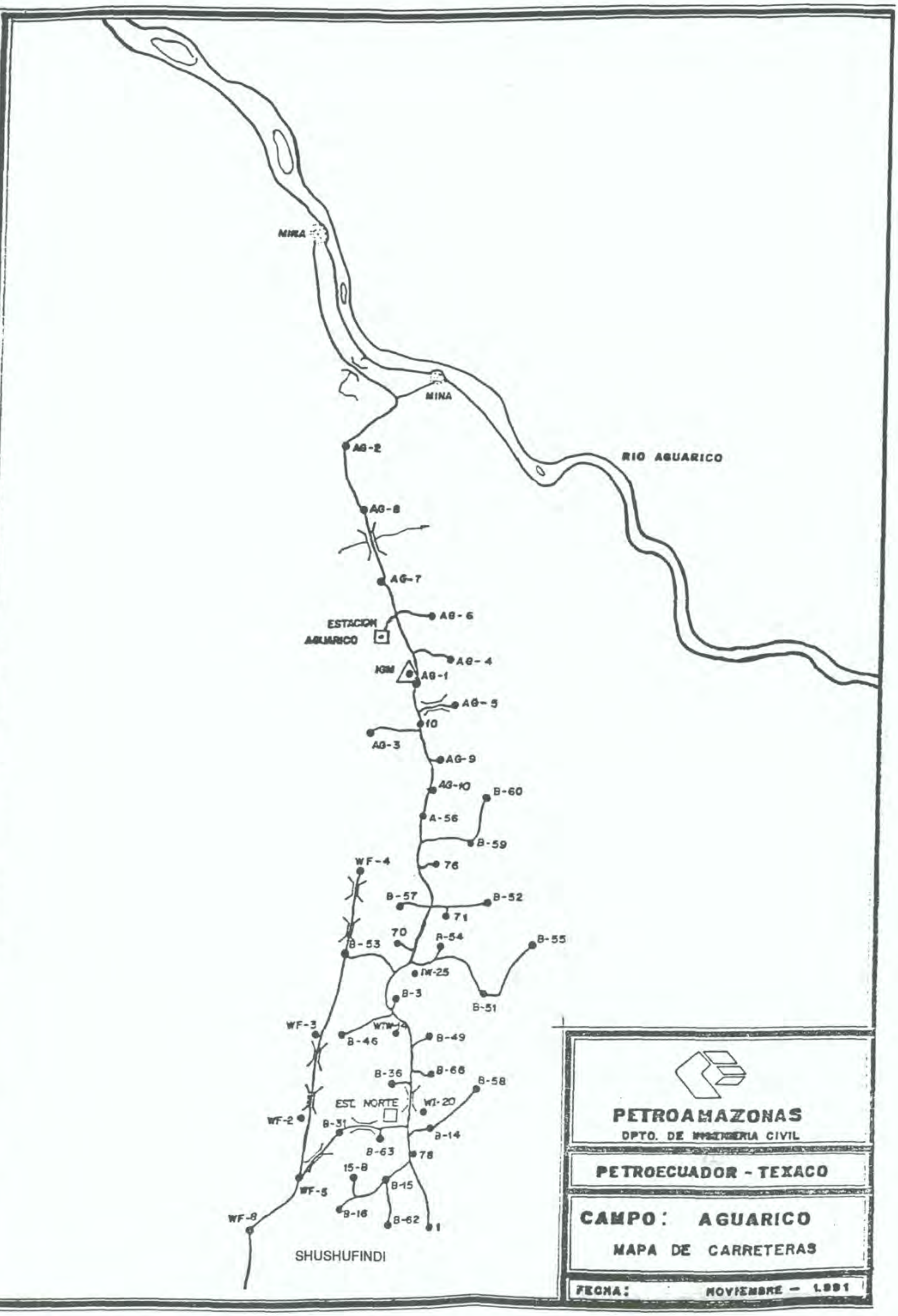
SIMBOLOGIA

SH — SHUSHUQUI
SC — SECOYA
S — SHUARA
P — PICHINCHA
C — CARABOBO
PAC — PACAYACU

PETROPRODUCCION
DPTO DE ING. CIVIL

CAMPO: LIBERTADOR
MAPA DE CARRETERAS

FECHA: ENERO - 94



PETROAMAZONAS
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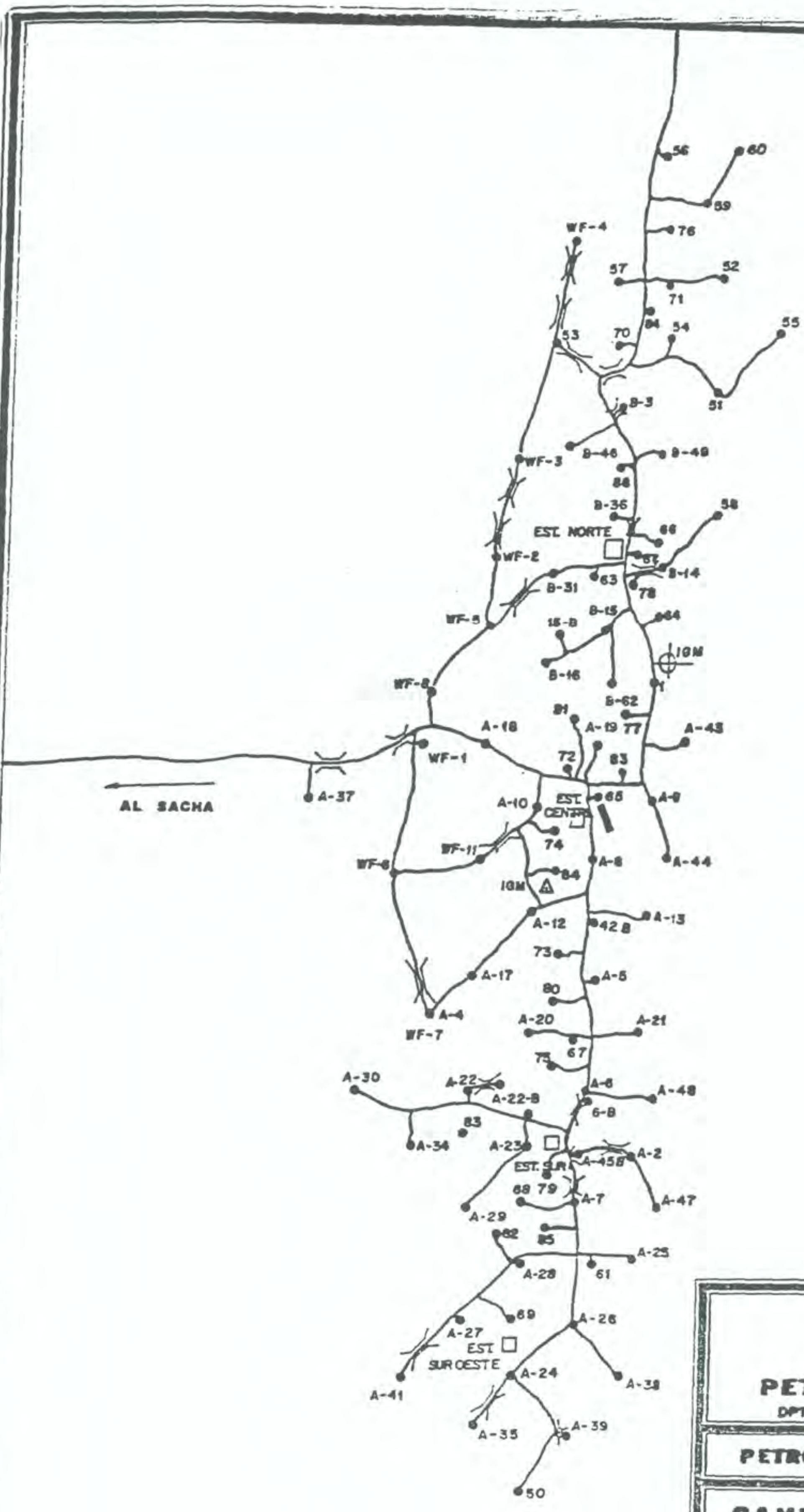
CAMPO: AGUARICO
MAPA DE CARRETERAS

FECHA: NOVIEMBRE - 1.991



PETROAMAZONAS

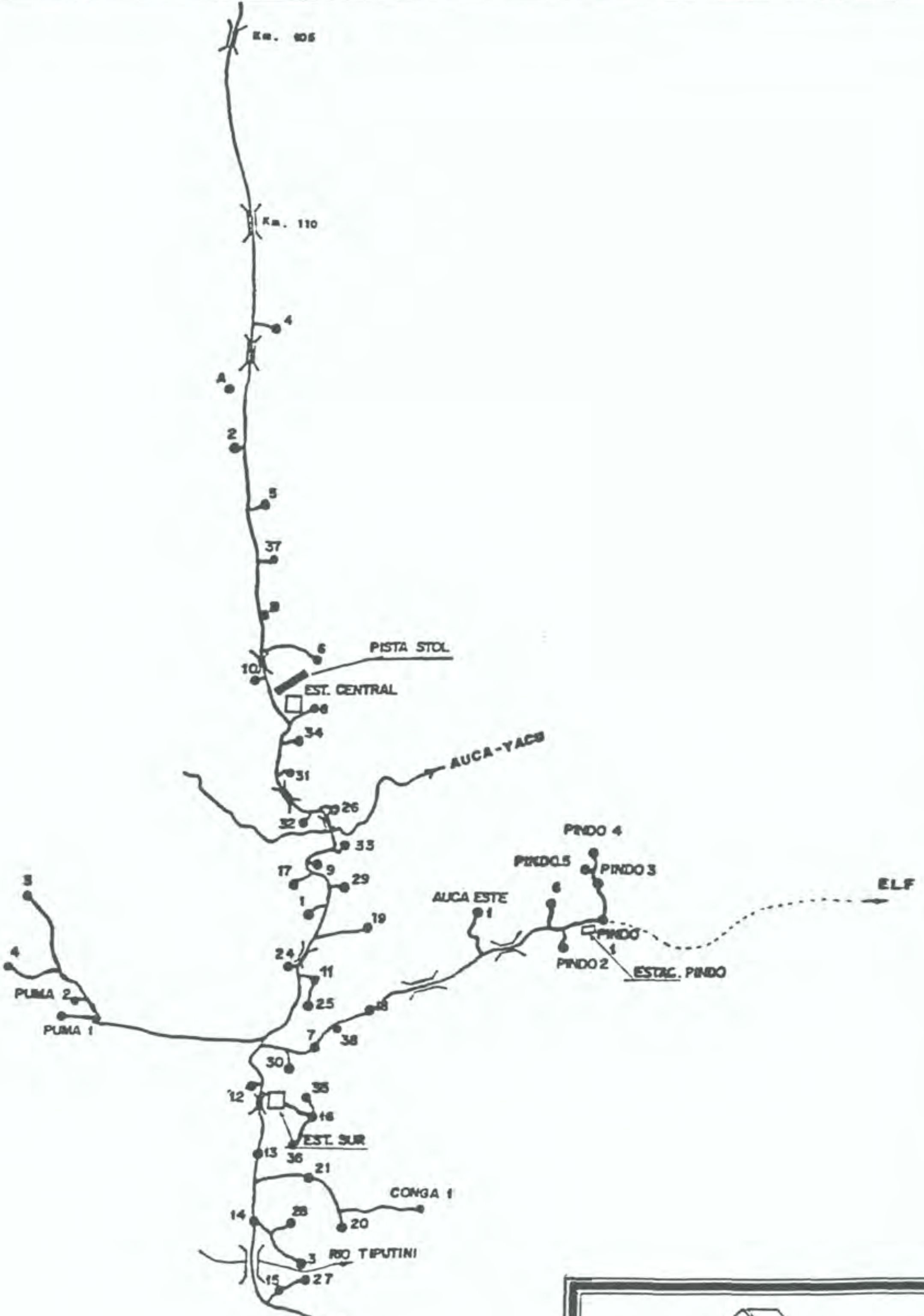
DPTO. DE INGENIERIA CIVIL

PETROECUADOR - TEXACO

CAMPO: SHUSHUFINDI

MAPA DE CARRETERAS

FECHA : NOVIEMBRE - 1.991



PETROAMAZONAS
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PETROECUADOR - TEXACO

CAMPO: AUCA

MAPA DE CARRETERAS

FECHA: NOVIEMBRE - 1.991

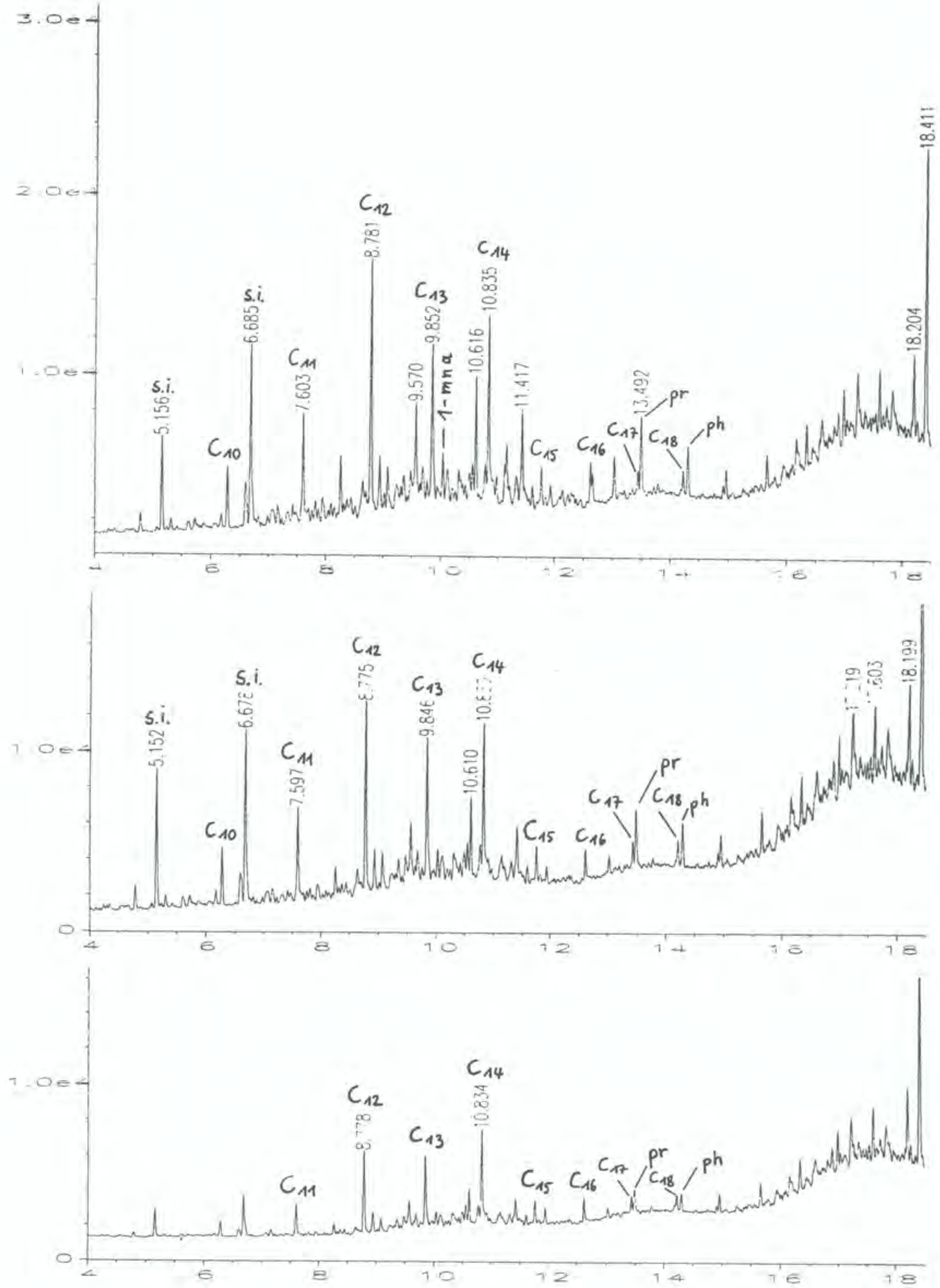

Fig. A2a. Gas chromatograms of Shushufindi crude oil after laboratory biodegradation under optimum conditions (addition of nutrients and oxygen). From top to bottom: day 1, day 3 and day 5 of incubation.

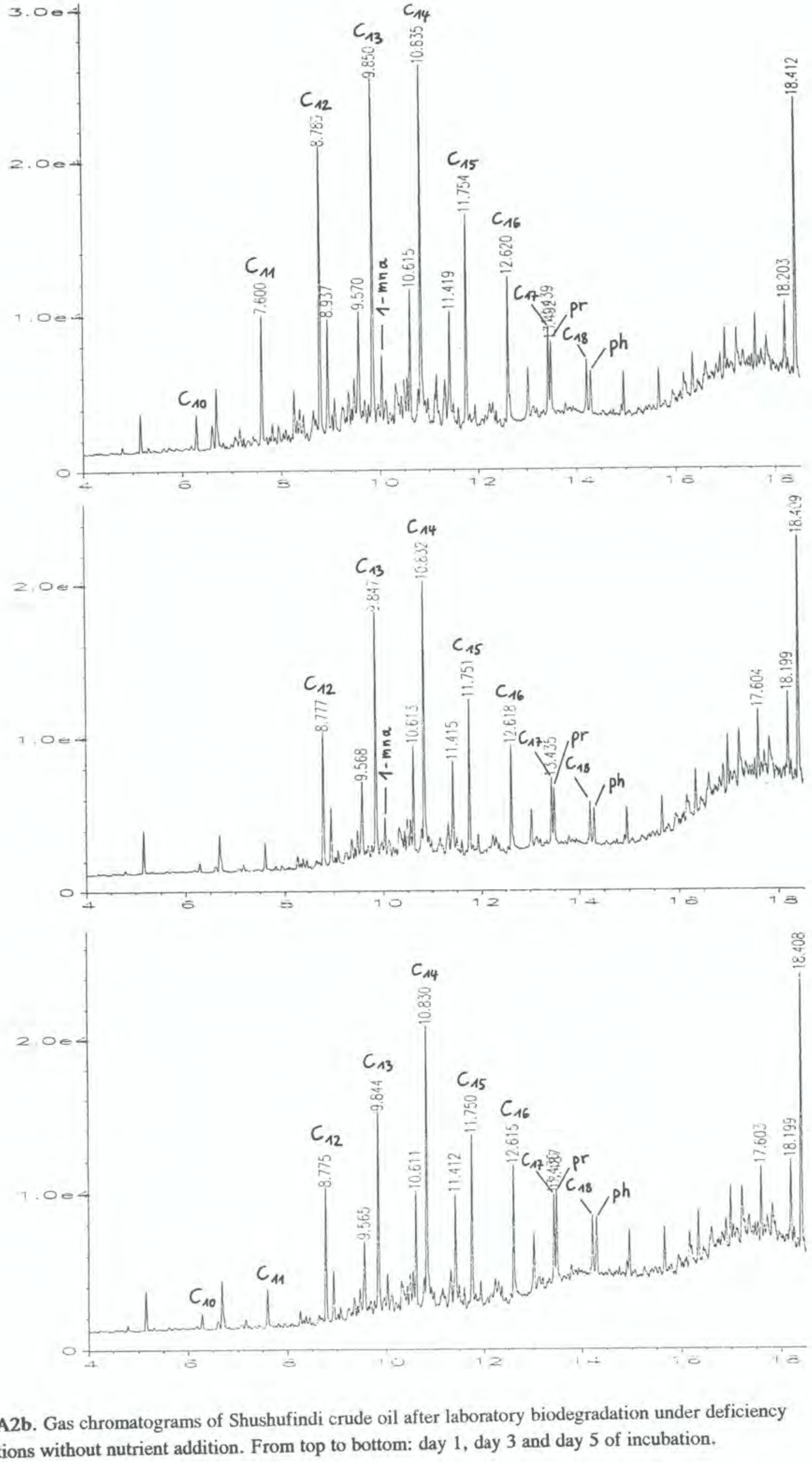

Fig. A2b. Gas chromatograms of Shushufindi crude oil after laboratory biodegradation under deficiency conditions without nutrient addition. From top to bottom: day 1, day 3 and day 5 of incubation.

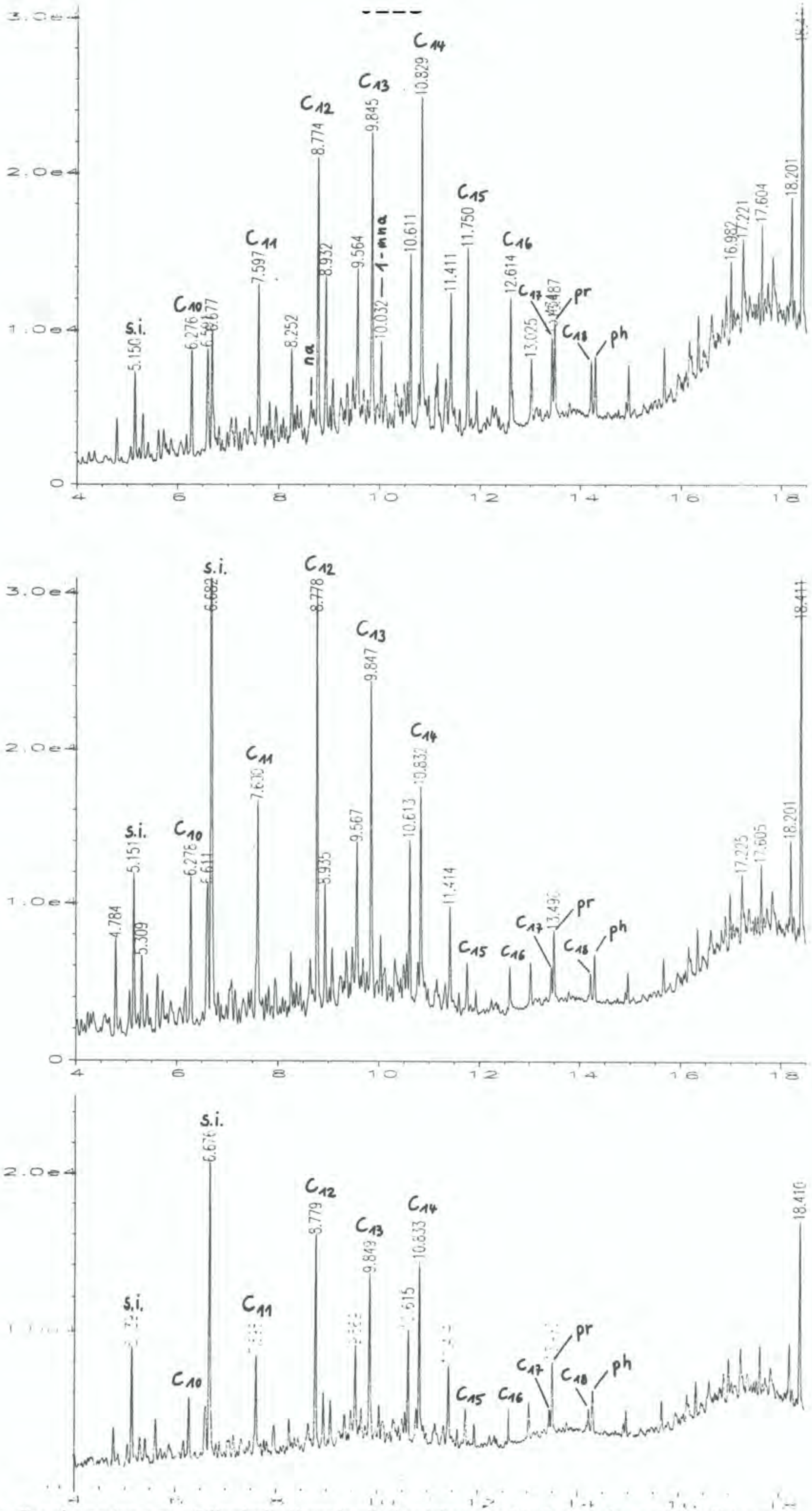

Fig. A2c. Gas chromatograms of Shushufindi crude oil after laboratory biodegradation under deficiency conditions without oxygen addition. From top to bottom: day 1, day 3 and day 5 of incubation.

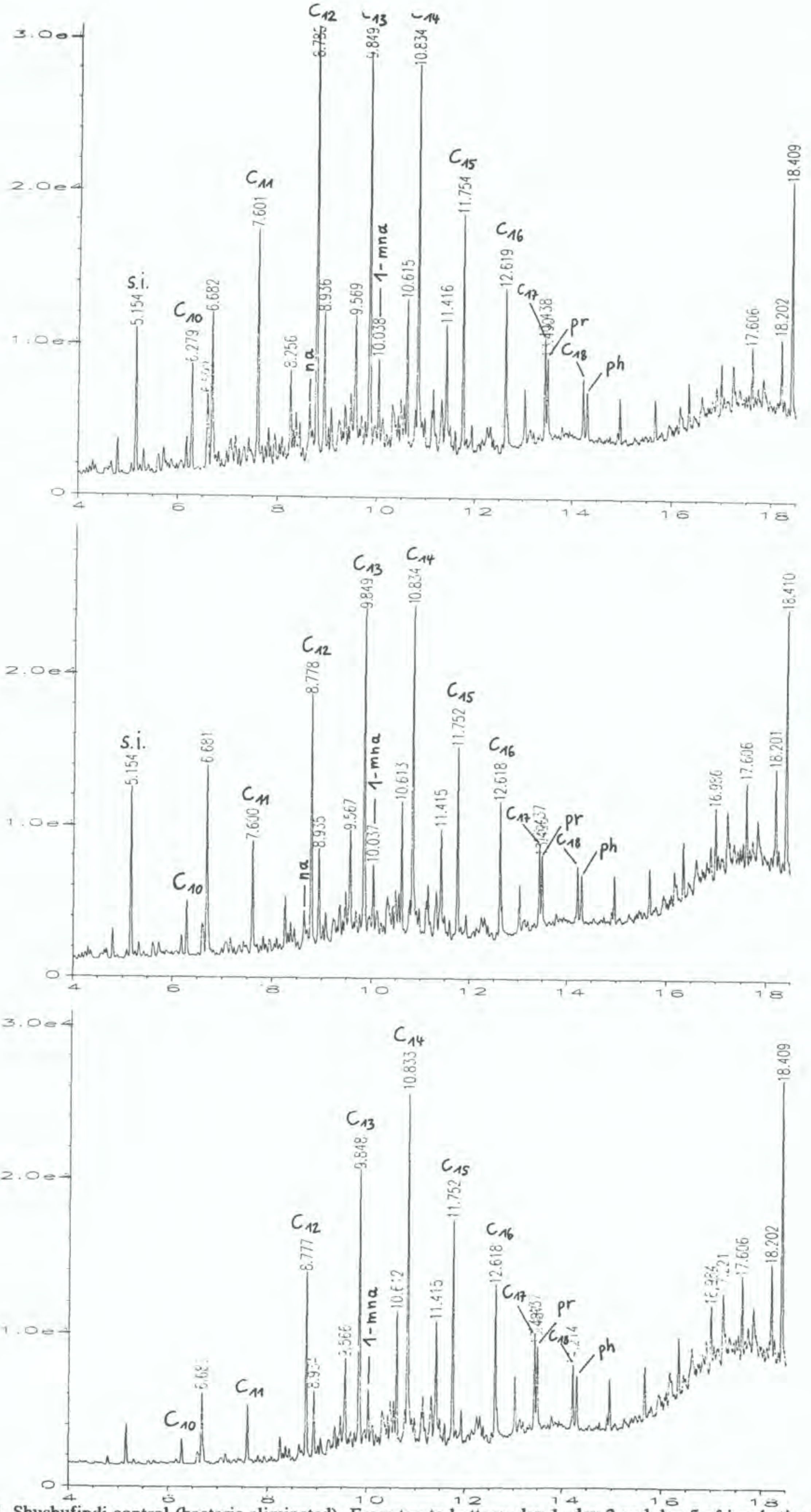

Fig. A2d. Shushufindi control (bacteria eliminated). From top to bottom: day 1, day 3 and day 5 of incubation.

ENGINEERING FOR DEVELOPMENT IN ENVIRONMENTALLY SENSITIVE AREAS - OIL OPERATIONS IN A RAIN FOREST

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ABSTRACT

It is possible to design and implement development projects in environmentally sensitive areas with the goal of minimizing adverse environmental impacts and maintaining the ecological integrity of the system. This requires designing the project around the constraints of the environment that supports it. Feedback from the environment (*e.g.*, in the form of reconnaissance studies or monitoring) is required both to design and operate the project. A case study of oil exploration and possible development in an Ecuador rain forest illustrates these principles and provides a possible model for development in environmentally sensitive areas. To accomplish sound environmental planning and management requires the collaboration of environmental scientists and engineers along with development of cost-effective methods and technology to predict and monitor environmental impacts. The academic community, funding and regulatory agencies, as well as potential "developers" should place a higher priority on implementing this cooperative process and strengthening the science base which supports it.

INTRODUCTION

Human populations and their support systems have expanded to the point that they can potentially affect global ecology. Perhaps the most significant impacts are the long-term ecological effects which result from human-caused disturbance, modification, and conversion of natural habitats. The result is that native plant and animal populations are reduced, confined to very small areas, or lost altogether. At some point the survival of species themselves may be in jeopardy. Most species become endangered or threatened not for genetic or physiological reasons, but because their habitat is modified or eliminated, or they are over fished or hunted.

Rapid human population increases are occurring in less developed, tropical countries, where biological diversity is greatest. Here, deforestation is resulting in the rapid loss of rain forest habitat and, potentially, species about which very little is known. Pressure on natural systems comes from basic survival needs for fuel and crop land and from the desire of the people and their governments to raise the standard of living, provide housing, promote industrialization and modern agricultural development. The problem is not confined to the developing world; industrialized countries are also losing natural habitats.

There is little hope of stopping natural habitat losses in the near-term. This is as true in the Santa Monica Mountains of southern California as in the forests of Brazil. Some important habitats can be protected in parks or reserves, but this strategy saves only habitat "islands" and, alone, cannot ensure maintenance of biodiversity over time. Solutions for the long-term must emphasize finding ways to maintain the ecological integrity and functions of "developed" areas. This approach is consistent with the concept of sustainable development (Lovejoy, 1994).

DEVELOPMENT THAT PRESERVES ECOLOGICAL INTEGRITY

The following are some examples of development that has resulted in protection of natural ecosystems and their biological diversity.

Camp Pendleton Marine Base in San Diego County contains many small wetlands that would have been converted to marinas and condos long ago had they not been on the military base. Because so many acres of wetlands have been lost to development in southern California, the small remaining wetlands at Camp Pendleton are increasingly important to coastal ecology.

Point Mugu Naval Air Station in Ventura County also supports many acres of wetlands, and some endangered species. In addition, because it is protected from disturbance, this is one of the few parts of the southern California mainland coast where seals and sea lions regularly haul out to rest.

Vandenberg Air Force Base in Santa Barbara County has some of the best rocky intertidal habitat in California, supporting the biodiversity that was present on the rest of the mainland many years ago.

The Guadalupe Dunes oil field in Santa Barbara County consists of oil wells, pipelines, roads, and some storage and treatment facilities. Because most of this coastal property is maintained in open space and public access is restricted, it is one of the last places in the region where native dune vegetation survives, including some endangered species. The dunes adjacent to the oil field are damaged by public use (dune buggies, dirt bikes) so that they no longer support native vegetation.

Similarly, in Kern County, California, oil fields are some of the only remaining large tracts of land that have not been converted to agriculture or urbanization. Here, too, native plants and animals are present, including several endangered species. One working oil field was recently designated an ecological preserve and is being managed as such, in cooperation with state agencies. This management will continue after the life of the oil field is over.

For these examples, protection of natural ecosystems was often an unforeseen byproduct of the type of development that occurred. However, now these environments are protected by design, as part of managing the facilities. It is the latter, environmental protection by design, that must be encouraged and supported. This process, environmental planning and management, is needed both domestically and internationally.

ENVIRONMENTAL PLANNING AND MANAGEMENT PROCESS

The goals of environmental planning and management are to minimize the adverse environmental impacts of development and to maintain or enhance the ecological integrity and functions of the natural system. The principles can be applied to development as diverse as an agricultural crop, housing tract, power plant, or oil production. Environmental planning and management is an interdisciplinary process involving the environmental sciences and engineering. It can be applied to ongoing operations or new projects, though it has its greatest effect when applied to new projects, early in their development when most siting, design and engineering options are still open.

Figure 1 illustrates the process. A project proposal is developed, including siting and design alternatives. An environmental reconnaissance study is conducted to identify the major ecological features of each site. This need not be, and in most cases cannot be, a lengthy and very expensive study. Much can be learned by knowledgeable scientists from a literature review, site visit, and study of topographic maps and aerial or satellite photos. On the basis of this information, an environmental impact assessment is prepared. This includes an analysis of the potential impacts of the various alternatives as well as recommendations of alternatives and mitigation measures. This information is fed back into an environmental management plan for the project siting and design process. The site and project design alternatives are selected and permits and other approvals obtained.

During the construction phase of the project, environmental monitoring is begun. Monitoring may begin prior to construction if additional, site-specific environmental data are needed. Monitoring to establish a "baseline" against which to measure future impacts is usually not feasible because of the time, scope, and cost of a study required to accurately define natural variation. The monitoring program must focus on environmental parameters and populations likely to be affected during the construction and operations phases of the project. Environmental impacts are assessed and the information fed back into an environmental management plan for the operations phase of the project. Monitoring continues to some degree during operations so that impacts can be assessed on a continuing basis and the management plan modified as necessary (figure 1).

Once this process is completed, the environmental and engineering information generated becomes extremely valuable to those planning similar development or planning a different project in a similar habitat. Therefore, dissemination of the results -- including both successes and failures -- is critical.

CASE STUDY - OIL DEVELOPMENT IN AN ECUADOR RAIN FOREST

Introduction

Tropical forests are complex environments that support a greater diversity of plant and animal species than any other terrestrial habitat. Most of these species (*e.g.*, insects) have not been named, described, or studied by scientists. Raven (1994) estimates that there are 8 - 10 million species on earth, only 1.4 million have been named. Tropical forests are also rich in substances, both medicinal and industrial, that are useful to their indigenous residents as well as society at large (Lewis, 1990).

Tropical rain forests receive 40-158 inches of rainfall per year. They typically consist of a relatively tight canopy of broad-leafed evergreen trees and two or more underlying layers of trees and shrubs. Undergrowth vegetation is usually sparse because little sunlight reaches the forest floor. Soils are typically acidic and poor in nutrients. Nutrient cycling depends on degradation of leaf litter, fallen trees, and shrubs on the forest floor. Because this cycle is so easily altered by disturbance, tropical forests are among the world's most sensitive environments (Wilson, 1988).

Acres of tropical forest are now being lost at such a rapid rate that a National Academy of Sciences Panel stated that most forests will not exist in their present form by the close of the century (NAS, 1980). The largest remaining contiguous tracts of tropical forests are in the Amazon drainage of South America and in central Africa. Deforestation in the tropics is also thought to influence local climate and contribute towards global climate change (Wilson, 1988). The ecology of humid tropical systems is poorly understood. Substantial research is needed to develop sustainable uses of these systems as well as methods to reduce impacts of development and restore damaged systems (NAS, 1982; NSB 1989).

The environmental impacts of development in the tropics are closely linked to socio-economic effects. Bringing development of any kind to semi-isolated indigenous populations brings profound changes to those cultures. Contact alone may expose communities to diseases for which no immunity has been developed. Alteration of the natural habitat may deplete or alter traditional food and water sources. When two cultures come into contact, the dominant culture will, in the long run, submerge the other culture unless protective measures are implemented.

It is in this context that ARCO International Oil and Gas Company is exploring for oil in Ecuador forests, part of the Amazon drainage (figure 2). This paper describes the major environmental and social issues relevant to the project (Lindstedt-Siva and Chamberlain, 1991), discusses some of the ARCO programs in place during the exploration phase, as well as current planning for the development phase of the project. These plans will be finalized and implemented if ARCO and the Ecuador government agree that the project will proceed to the development phase.

Major Environmental and Social Issues

Deforestation and Habitat Alteration

Deforestation and habitat alteration are occurring rapidly in the tropics, world-wide. Historically, the primary cause of deforestation has been invasion by colonists who clear the forest to raise cattle or grow crops. Governments have also "opened" new areas, encouraging colonization and other types of development. Roads are the major contributor to deforestation. Wherever roads have been built into previously isolated areas the result has been invasion by "outsiders" followed by deforestation and environmental degradation as well as profound social impacts.

Pollution

Environmental pollution is a lesser, though potentially significant issue in the tropics. When vegetation is removed and heavy equipment used there is a high potential for erosion and contamination of streams used for drinking water as well as fishing. Garbage, sanitary and exploration/production wastes are potential sources of contamination that could be significant in this sensitive environment. Air pollution associated with operations may be locally significant.

Social impacts

In the past, when areas of tropical forest were "developed," the overall results were often detrimental to indigenous people. Uncontrolled, spontaneous colonization by outsiders often displaced the local populations and introduced diseases. Colonists in all parts of the developing world have been tenacious and relentless. Stopping them is extremely difficult, especially when there are roads into an area. Social consequences may include displacement of indigenous people and degradation or depletion of resources needed for survival (drinking water, native plants and animals), erosion of culture, alcoholism and other ills, and the possibility of making communities dependent upon the outside world with no way to maintain or return to traditional ways if outside support systems are removed.

Exploration Phase

Background

Oil exploration and production in Ecuador began early in the Twentieth Century. ARCO International Oil and Gas Company (AIOGC), a division of ARCO (Atlantic Richfield Company), began exploring for petroleum in Ecuador in November 1988. The ARCO project is Block 10 in the Oriente, a part of the Amazon rain forest east of the Andes mountains (figure 2). ARCO International and its partner, AGIP (Overseas) Ltd., are service contractors for the Ecuador state petroleum company, PetroEcuador, by an agreement signed in June of 1988. Block 10 is 200,000 hectares (494,000 acres) in size. Other oil companies are operating in similar blocks in areas north of Block 10.

Between November 1988 and July 1989, seismic exploration was conducted throughout the block (figure 3) except in the extreme southwest corner where operations were discontinued in deference to the wishes of indigenous people living in the area. Seismic lines as well as footpaths and helipads needed to support the seismic operations were cleared by hand (chain saw and machete) and occupied an estimated 341 acres. A subsequent seismic operation conducted between August 26 and September 29, 1991 resulted in hand clearing an additional 14.4 acres.

Three exploratory oil wells were drilled at two approximately 4.5 acre sites, Moretecocha and Villano, named for nearby villages and chosen with assistance from the villagers. One well was drilled near Moretecocha and two near Villano. Oil has been found at both locations. A fourth exploration well is proposed for a site in the vicinity of Villano and possible pipeline routes have been surveyed.

Environmental and Social Strategies

A major goal is to minimize the environmental and social impacts of the project. Environmental guidelines for rain forest operations were developed by AIOGC in conjunction with corporate biologists (AIOGC, 1990). Major elements include:

1. Minimize the "footprint" of all operations (seismic lines, helipads, camp sites, drill sites) - the smallest footprint possible minimizes vegetation removal and reduces all environmental impacts accordingly.
2. Minimize the use of heavy equipment (tractors) -- use hand methods (machete, chain saw) when vegetation must be removed. Natural restoration of disturbed areas is much faster if the topsoil is not disturbed.
3. No new roads - move all equipment and personnel using existing out-of-forest roads, aircraft, or on foot.
4. Consult with local communities -- informing and involving residents of villages nearest to and most affected by the project is vital. Local villagers select trees to be used in construction, participate in cutting lumber, and advise AIOGC on a variety of environmental and social issues.
5. Restore disturbed sites.

Lumber Harvesting and Transport

Drill sites were designed to be smaller (4.5 acres) than those commonly constructed in the area (approximately 12 acres). Trees to be used for lumber needed to construct drill pads were selected by local Indians and cut by hand (no clear cutting) at remote locations. Boards were then transported to the construction site by helicopter. This method of lumber harvest and transport is unconventional and greatly reduced the ecological impacts of the project over what it would have been if lumber were harvested using heavy equipment and transported on roads (the conventional local practice). This selective harvesting method closely mimics natural tree falls which clear a small area, allowing sun to penetrate the forest canopy. This is followed by growth of sun-tolerant species, the first stage of the succession process that leads to natural restoration of the forest (Brown and Press, 1992).

Construction and Use of Heavy Equipment

Construction of drill sites for exploratory wells and associated operations was the only part of the project which required the use of heavy equipment. The drilling rig and supporting heavy equipment were brought to the site in sections, by helicopter, and assembled at the site. After construction and drilling were completed, all equipment was disassembled and removed by helicopter.

Reclamation

Natural recovery of helipads, seismic lines, and camp sites was rapid because vegetation was cut by hand (using chain saws and machetes) and top soil was not disturbed. Where heavy equipment was used to construct drill sites, recovery takes more time. Reclamation programs were implemented to enhance the recovery process. Top soil removed to construct drill sites was retained on site. Nurseries were established at each site to provide native plant seedlings. The initial phase of reclamation is complete at the Moretecocha site, and monitoring indicates that additional work may be desirable. A reclamation program incorporating what was learned at Moretecocha is now underway at the Villano site where two and one-half years of drilling has just ended.

Development Phase

Introduction

As of this writing, ARCO International and AGIP are preparing a field development plan which the government of Ecuador will use to decide whether or not the project should proceed to the development phase. In anticipation of development, a number of environmental studies and planning exercises took place. Whether or not the project proceeds, the ideas and strategies that emerged from this process have broken new ground and provided what may be a model for development in environmentally sensitive areas.

Conventional Technology and Approaches

Conventional development of an oil field requires construction of drill sites, pipelines, gathering and processing facilities, pump stations. Technology and construction methods for these facilities are well established and accepted in the industry and are currently common practice in Ecuador (figure 4A). Drill sites in this area have historically occupied approximately 12 acres. They are connected to one another and to support facilities by roads. Pipelines are necessary to transport oil from wells to gathering and treatment facilities for shipment out of the area (most often by pipeline). Pipeline construction requires road construction first, so that equipment may be moved to the site. Roads are also required for access after the pipeline is complete. Pipelines are typically monitored using aircraft, requiring that pipeline corridors be cleared of vegetation so that leaks or other problems may be detected from the air. Workers in remote oil fields are normally housed in base camps near the facilities. This requires not only housing oil workers but support personnel (*e.g.*, food and hotel services) as well.

Environmentally-Based Technology

During planning, several questions were asked. Can alternate approaches be developed that will reduce environmental and social impacts of the project over conventional approaches? Since we know that roads are a major cause of environmental and social impacts in rain forests, is it possible to construct an oil production project without roads? Can alternate methods be found to construct and monitor a pipeline without roads and without breaking the forest canopy?

When we first started asking these questions, the nearly universal response was that it is not possible to develop a project without roads, a project that would be completely different from anything that had gone before. At a minimum, a roadless project was expected to be very costly. The more the questions were studied, however, the more likely it looked that at least some of these goals could be achieved. The following are descriptions of concepts that emerged from these studies.

The Offshore Model

The goals of a small footprint, roadless operation caused the project team to search for an alternate model to conventional oil field development technology, *i.e.*, oil production without roads. The key breakthrough in our thinking came when the project leader visualized oil production in a rain forest using the only current example of oil production without roads, an offshore operation (figure 5). The remote, tropical rain forest setting is directly analogous to a remote oil discovery offshore. If the offshore model is applied to this onshore situation, many of the same practices and development techniques used by ARCO in open waters could be applied cost-effectively to the rain forest operating environment.

Refining the Offshore Model

Conventional onshore development with a road was evaluated to give baselines for development and construction time, cost, and risk as well as the socio-environmental impacts. This approach was evaluated against conventional offshore development as well as variations of the offshore model.

The conventional offshore approach is to house personnel on platforms, along with oil, gas, and water processing facilities. Logistical support for the platforms (*e.g.*, crew and equipment transport) is provided by air or work boat. The rain forest version of this approach would be to locate processing facilities and support personnel quarters in a compact design at the drill site with logistical support by air.

The second alternative evaluated is production processing in the field with support personnel housed remotely (at the nearest village). This hybrid concept allows for location of oil, gas, and water processing at the oil field as in a conventional development combined with the offshore approach to logistics and support.

A third alternative, locating production processing facilities and worker housing at the nearest community along the oil pipeline route, is the current preferred model (figure 4B). Here there is access to electric power, roads to urban areas, an existing support system for oil field workers, including housing, and telecommunications. The equipment and systems at the remote oil field are minimized and as simple, reliable, and durable as possible. This approach concentrates people at the population center and reduces the number of people in remote locations of the oil field.

Production Processing Technology

Conventional oil field technology used to separate and treat produced oil, gas, and water is complex, requiring close monitoring and maintenance (figure 6, case 1). Project engineers studied various alternatives (figure 6, cases 2 and 3) and finally developed a simpler, low maintenance alternative (figure 6, case 4). This alternative minimizes the footprint of the project as well as numbers of workers required to support it, thereby minimizing environmental impact. No road access means protection from colonization by outsiders and maintains local control. The indigenous communities will continue to manage their lands and resources and can make the deliberate decision to discourage or encourage entry of colonists and other industries and agriculture if they desire. In addition, since company and contractor personnel will visit the field on an as needed basis only, greater control of cultural evolution will be exercised by the indigenous people themselves. There are possibilities for long term employment of local people, if desired. Further, with flexibility designed into the pipeline, power, and processing systems, future discoveries can be integrated into this plan with continued minimal impact.

Costs

Costs for a remote operation are increased over conventional technology for the construction phase, but may be reduced over conventional technology for operations because of the smaller number of personnel that must be maintained at remote locations and the simplicity and lower maintenance required for production equipment.

Pipeline Options

Many pipeline options are being evaluated during the planning process. The only constraints placed on engineering teams are: (1) 30,000 barrels per day will be moved out of the field, (2) there will be no permanent road leading to developed areas and, (3) the cleared right-of-way will be less than 20 feet wide, rather than the conventional 60 feet. During brainstorming sessions, numerous innovative techniques for constructing and monitoring the pipeline emerged.

Land Pipelay "Barge"

One of the more unusual concepts was to design a land pipelay "barge." Constructing a pipeline offshore requires a specially made barge which transports the pipe to the offshore location, welds, wraps, inspects, and lays the pipeline on the sea floor. We thought that we could minimize tree removal by designing a "barge" of multiple platforms linked together. The right-of-way for the pipeline would be slightly wider than the "barge" since each platform would straddle the pipeline ditch. Each platform would serve a separate function. The lead unit would trench the ditch. The second unit would carry the sections of pipe and feed them one by one into the automatic welding machine. The third unit would quench and wrap the pipe. The fourth unit would inspect and drop the pipeline into the ditch. The fifth unit would refill the ditch. Using retired military tracked heavy vehicles, this concept may yet be viable.

Manual Construction

Using manual labor to construct the pipeline would reduce the need for heavy equipment and roads. This approach would require either laying the pipeline on the surface or digging the ditch by hand. A surface line would minimize tree loss and corridor width. However, conventional fifteen to twenty-four inch diameter pipe is difficult or impossible to move by hand. In addition, welding machines are required to connect the 40-foot sections. To solve this problem, high pressure plastic pipe could be used, fused together with machines that can be carried by humans over rough terrain. Alternatively, two smaller parallel pipelines could be installed rather than one larger one. The smaller size pipe would be easier to handle in the field.

Flexible Pipe

Another approach is to use flexible, armored pipe such as is used offshore. This pipe is reinforced, high-pressure rubber hose wrapped in a metal sheath. Long sections of this pipe could be flown along the pipeline route in coils, uncoiled and connected by hand, and laid around the larger trees.

Double Pipeline

Consideration was given to a double pipeline with oil flowing through the center pipe and monitoring equipment in the space between the small and large pipe. Such a double walled pipe could be laid in the Villano River. This would minimize vegetation removal and soil disturbance during pipeline construction as well as the need for roads to transport equipment.

Temporary Roads

To avoid constructing a permanent road along the pipeline, it may be possible to build temporary roads which would be removed after pipeline construction. Temporary roads could be made from reusable materials, *e.g.*, surplus military aircraft runway steel plating or "lumber" made from recycled plastic waste. This material could be moved along the pipeline route and used as road surface for the heavy ditching and pipe-moving equipment. In many places temporary bridges could be used to eliminate permanent river crossings.

Tunneling

The terrain may require boring through some small hills, under streams, or from the top to the bottom of escarpments. Sections of the pipeline could be laid in these small diameter tunnels to eliminate permanent bridges and impede the crossing any of these natural barriers by off-road vehicles or horse-drawn carts.

Corridor

Using these concepts, it may be possible to design the pipeline so that the right-of-way is 20 feet or less. With a corridor of this size, the natural forest canopy may not be broken.

Pipeline Monitoring and Maintenance

Once the pipeline is laid, it must be monitored for breaks, corrosion and leaks. Normally, a pipeline route is observed by periodic over flights using a small airplane or a helicopter. If this pipeline is constructed using techniques that allow the forest canopy to remain unbroken, airborne observation will not be possible. Again using the offshore model, flow meters could be used to monitor the volume of oil in the pipe at various points. Pressure monitors can be used to detect leaks. As is the case in all major pipelines, instruments ("pigs") are placed in the pipe to clear the line of extraneous fluids and monitor corrosion. To take the place of aerial observation, local indigenous people who live along the route could be hired to walk the line and look for leaks or damage.

Selecting an Approach

Some of these concepts may be viable and find their way into the project. Availability of materials such as super high pressure plastic pipe or the feasibility of "land barges" will be a factor. Cost will also be a major consideration, *e.g.,* reinforced flexible pipe would be extremely expensive and may not even be available in the large diameter required. However, exploring ideas such as these has enabled project personnel to completely rethink the process of constructing, maintaining, and monitoring a pipeline.

CURRENT STATUS OF ENVIRONMENTAL PLANNING AND MANAGEMENT

The type of environmental planning and management described here is not widely practiced, even in developed countries. Yet, if we hope to conserve natural ecosystems and reduce the rate of loss of biological diversity, sound environmental planning and management is critical. The process need not be lengthy or expensive to apply. The key for the long term is adequately trained, in-country environmental scientists and engineers, working together. There are short- and long-term opportunities for technology transfer.

SCIENCE AND ENGINEERING NEEDS

Environmental Monitoring

Environmental planning and management is based on getting information from the environment and feeding it back into the management plan of the project. We must find better, less expensive and time consuming ways to obtain this information. Neither industries nor government regulatory agencies have the resources (time or money) to do long term, "baseline" type studies. For most development projects around the world, resources will not be available to support the type of environmental studies that are routinely conducted in North America and Europe. Yet accurate environmental data, useful in the project management process, are needed. Since it will not be possible to study everything, we need to develop methods that focus on those parameters that will tell us most about the environment at least cost. We need to develop scientifically valid "short cuts." Are there different/better ways to make use of satellite-generated data and aerial photography? Can some populations be used as "indicators" of environmental quality to eliminate the need to monitor all populations (*e.g.*, birds, butterflies)? Are there some stages of the life cycle (*e.g.*, larvae) more appropriate to monitor than others? What physical parameters would give us the most information about the environment at least cost?

Durable, low-cost instrumentation is needed for environmental monitoring from temperature probes to current meters to animal collars that use satellite telemetry for tracking. The extent to which monitoring can be automated and equipment is made to be durable and easy to use, will determine its usefulness in project management.

Ecosystem Restoration/Creation/Enhancement

One way to reverse the losses of natural ecosystems is to restore damaged systems, create new systems and enhance existing systems. Many programs are underway currently to create or restore wetlands. Some projects have successfully restored natural forest habitats. Experiments have been conducted on enhancement of marine ecosystems by building "artificial reefs." There is a great need to develop methods to restore, create and enhance ecosystems and to strengthen the science base underlying them. This includes careful monitoring of projects and dissemination of the information, whether they succeed or fail. In some cases, *e.g.*, wetlands, regulations are ahead of science. To support the national goal of "No Net Loss" of wetlands, regulators may require wetlands creation or restoration as a condition of permitting activities in wetlands. However, issuing a permit does not necessarily make it possible to create a functioning wetlands ecosystem. Generally, more funding agency support and more attention from the academic community are needed to support the emerging field of restoration ecology.

Training

Environmental planning and management is not an area that is emphasized in academic curricula in ecology or engineering, the two major disciplines required to practice it. Courses in this subject should be available for majors in both of these disciplines. Few universities require classes in ecology for engineering students or engineering for ecologists. To create an environmentally compatible development, engineers must have a basic understanding of the environments in which they will be working and environmental scientists must learn some of the language and constraints of engineering. Sound environmental planning and management requires the cooperative interaction of these disciplines. It would aid the process if this interaction began during the training of its practitioners. It is important to build a base of environmental planners and managers in all countries.

Information Dissemination

Efforts by all industries and government agencies participating in the environmental planning and management process are needed to disseminate the information gained from development projects. The possibility of a central bibliographic database should be explored.

DISCUSSION

If there is a chance to preserve natural habitats and the biodiversity they support, it will not be enough to focus on creating parks and refuges and conducting biological surveys. Parks and refuges are of value in that they preserve samples of diversity. Inventories are essential, but they document what is being lost while doing little to reverse the trend. A long term solution to the problem requires that more attention be given to land that will be "used," *i.e.*, to develop methods that allow use of the land while maintaining its ecological integrity and functions. This is not an area that has received much attention from the academic community or national funding agencies. Few "developers" (from slash and burn colonists in the rain forest to housing developers in the USA) have the resources to conduct the long term studies required to even inventory species present, much less gain a complete understanding of the systems in which the development will take place. Yet ecologically-based management methods must be applied if natural systems are to be maintained outside parks and preserves.

The following are examples of questions that need the attention of the research community and funding agencies.

Will undisturbed corridors in the midst of a development maintain the overall ecological integrity of the system? How large should corridors be? What configurations?

Which has less ecological impact overall, high density or low density housing? What are the tradeoffs?

What kinds of monitoring can best and most cost effectively indicate when an activity is damaging an ecosystem? When is a damaged system "recovered?" Is it possible to determine when a "restored" system is self-sustaining?

How clean is clean in the ecological sense? For example, in cleaning up an oil spill, is ecological recovery faster if some oil is left in the environment rather than using extreme measures, such as high pressure hot water, to remove it?

Are there methods to restore damaged or degraded habitats more effectively than natural recovery? Which methods are ineffective or actually increase damage or prolong recovery?

These questions identify areas of research and reporting that have "fallen through the cracks." They are not seen as a mission by any agency or funding group. Yet there is a great need to develop the science base in these areas that have very practical and immediate application. To develop the methods requires the collaboration of environmental scientists and engineers, much the way in which AIOGC developed unconventional strategies for its Ecuador development project. One further element is required for implementation of sound environmental planning and management practices, *i.e.*, a supportive regulatory framework.

CONCLUSION

The Villano Field oil discovery in Ecuador is requiring ARCO to become extremely innovative in designing an exploration and development plan with the goal of minimizing environmental and social impacts. By applying lessons learned from oil operations around the world and encouraging creative technical thinking, a plan is being developed which is operationally sound, cost-effective, and proven by application in an offshore environment. It is also consistent with the environmental and cultural objectives of the company and the indigenous people in the area.

A major effort is needed to strengthen the science base as well as train and encourage scientists and engineers to practice the innovative thinking and collaboration required to implement sound environmental planning and management. Environmental scientists and engineers in the academic community must develop programs to promote this field. Industry scientists and engineers must be empowered to take risks and think unconventionally, it is through them that most new ideas will be generated and applied in the field. Governments need to develop regulatory frameworks that support, rather than impede, this process. Supporting and encouraging sound environmental planning and management offers some hope that the ecological integrity and functions of natural systems may be maintained when development occurs.

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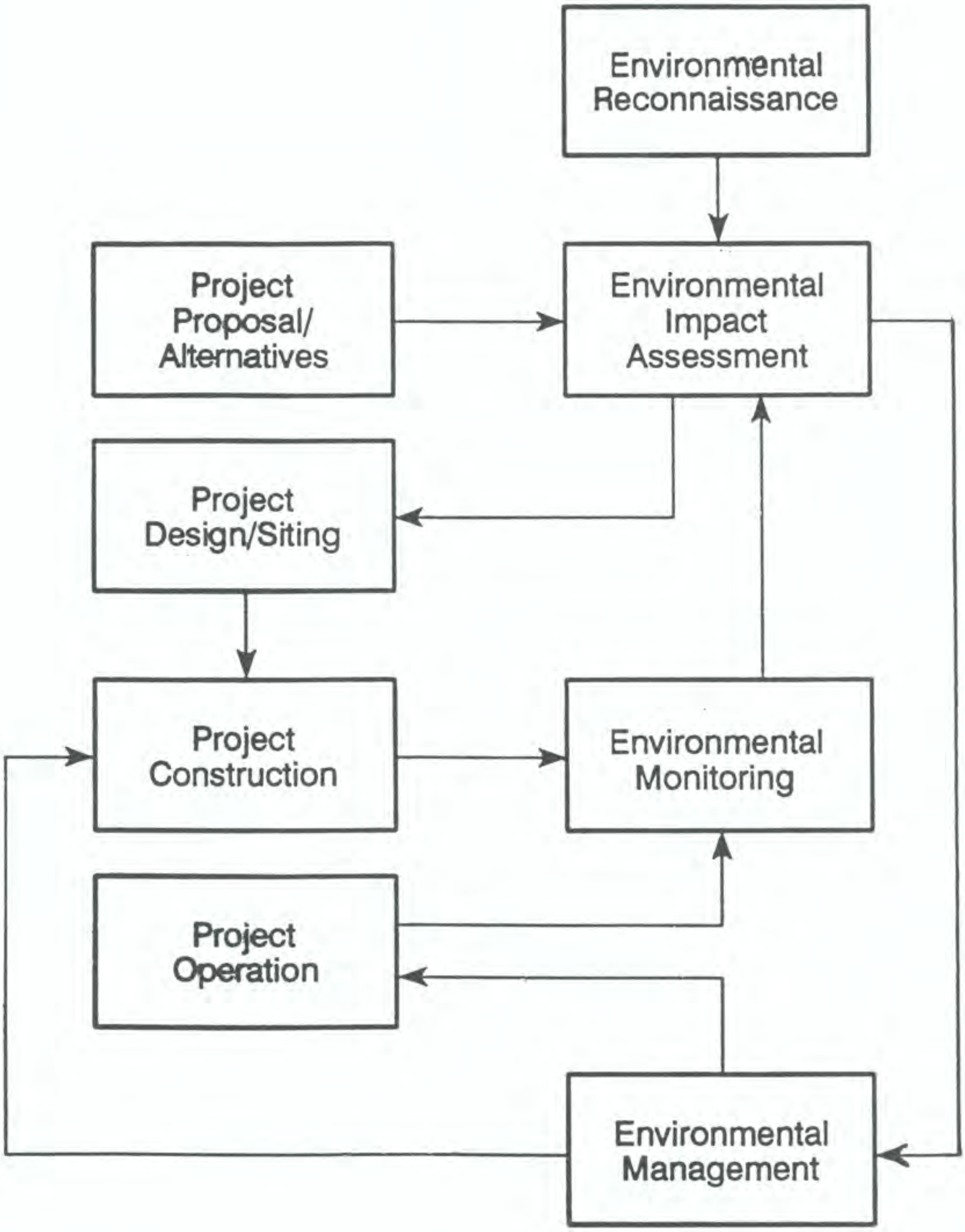


Figure 1. Environmental Planning and Management Process

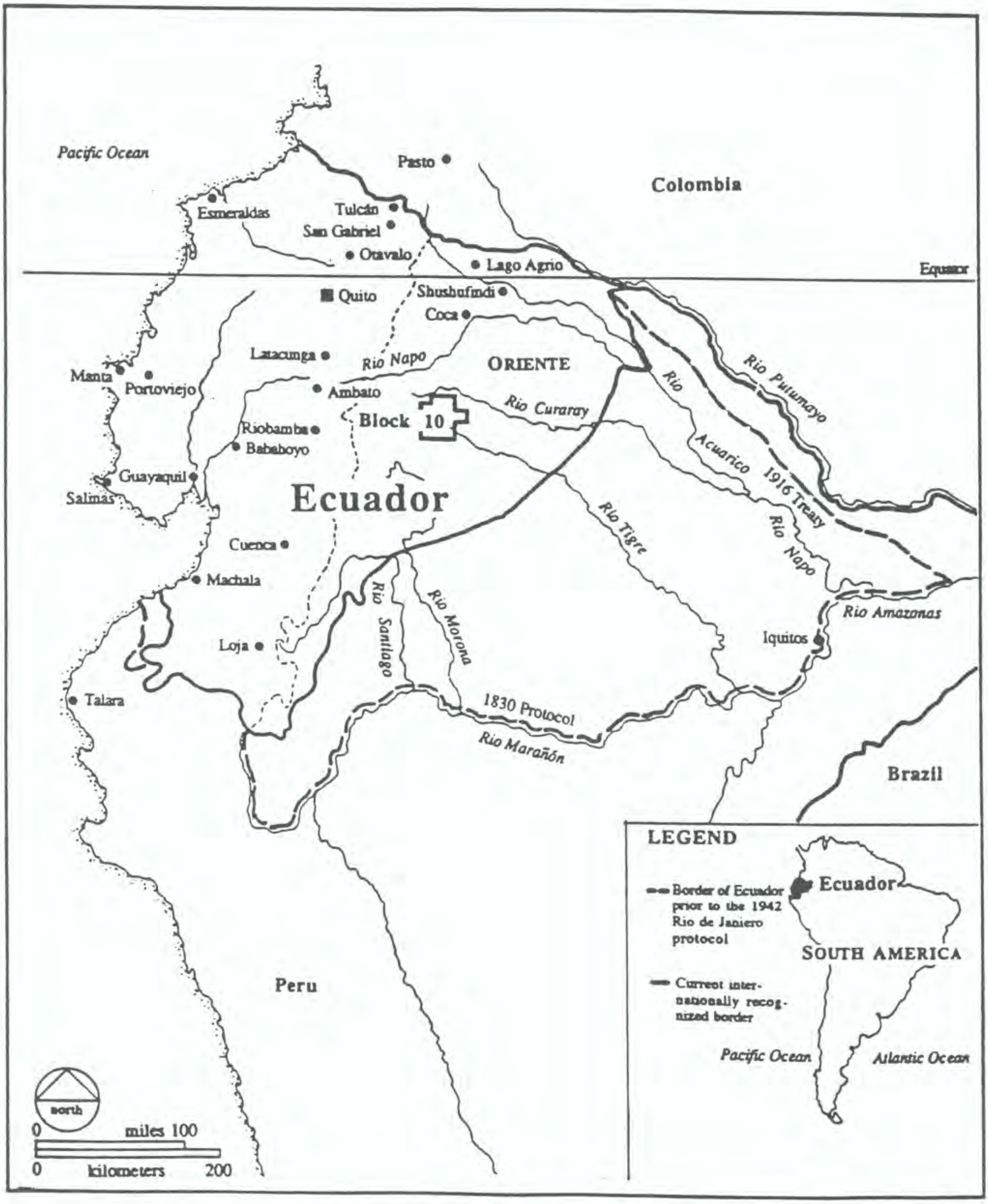


Figure 2. ARCO International Oil and Gas Co., ARCO Oriente, Block 10, Pastaza Province, Ecuador
(From McCreary *et al.*, 1992)

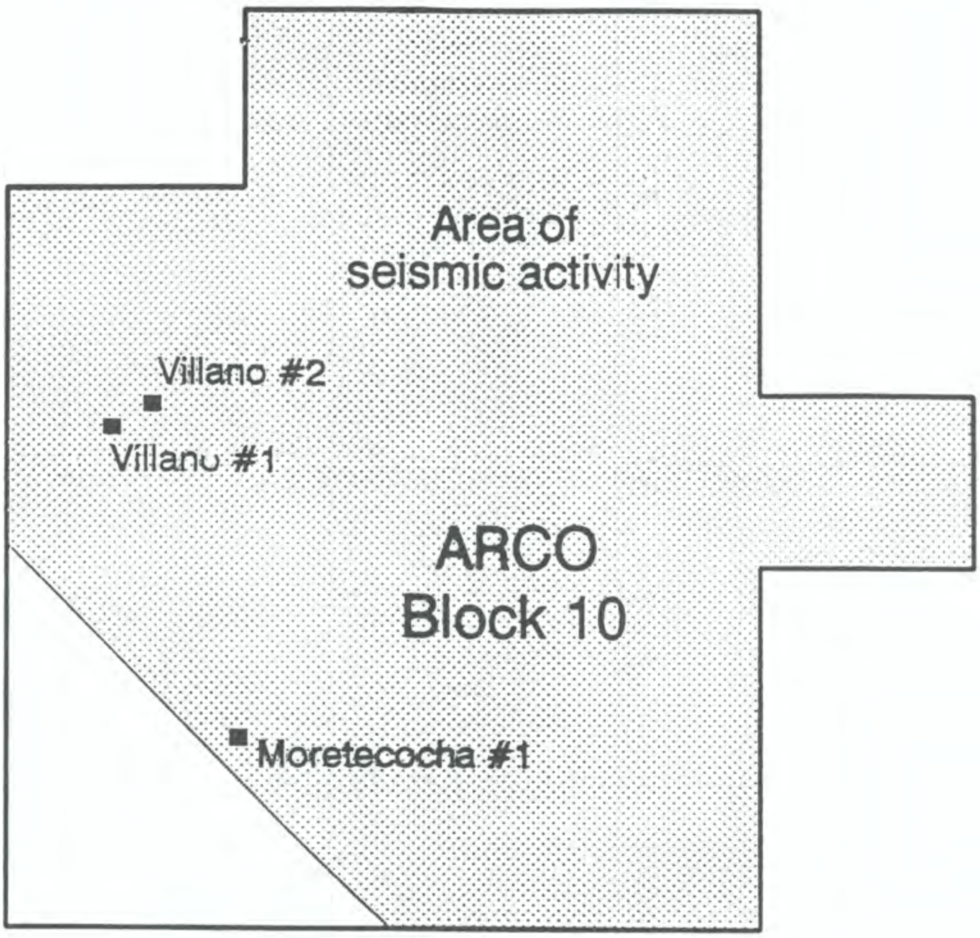
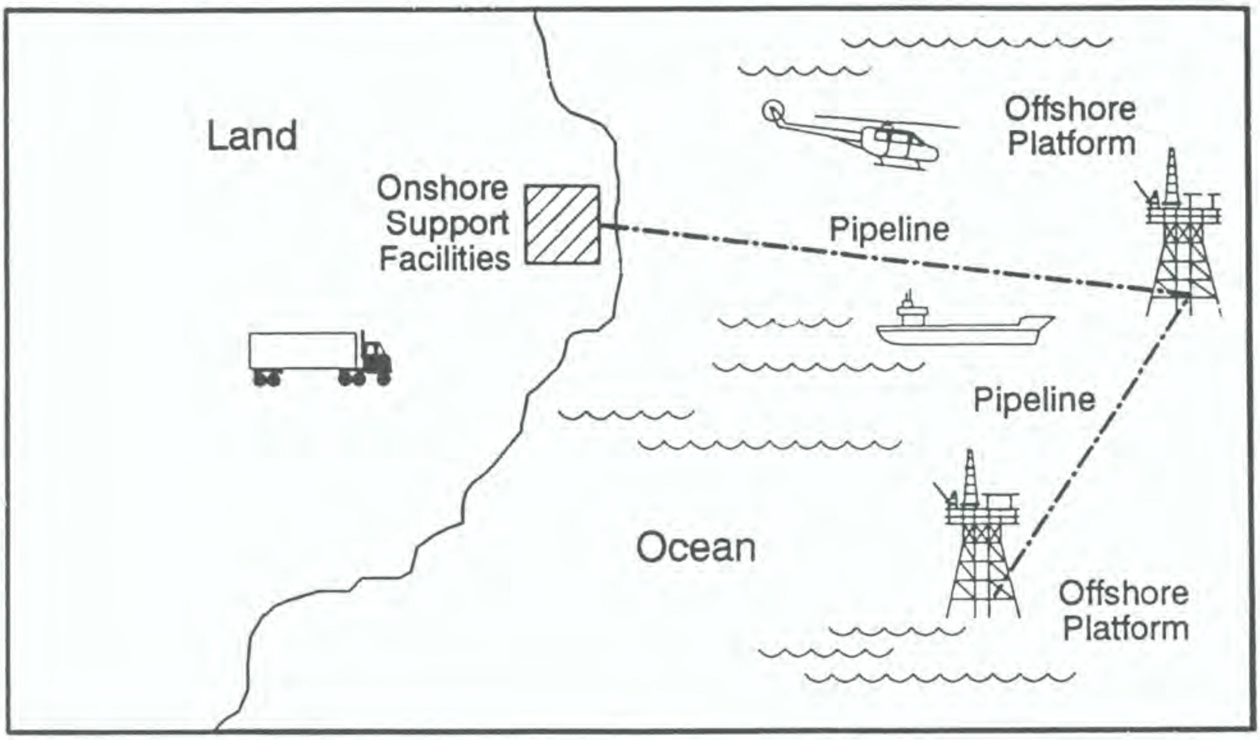
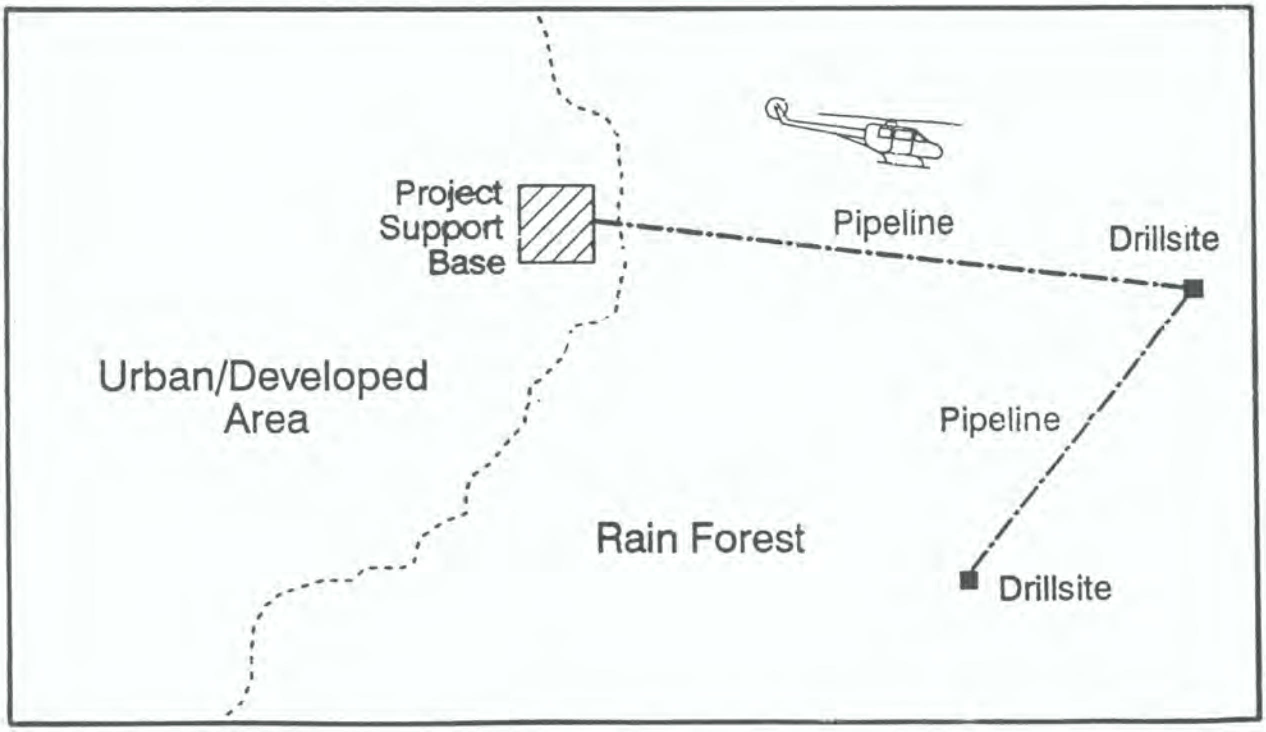


Figure 3: Seismic operations and exploratory well sites, Block 10.



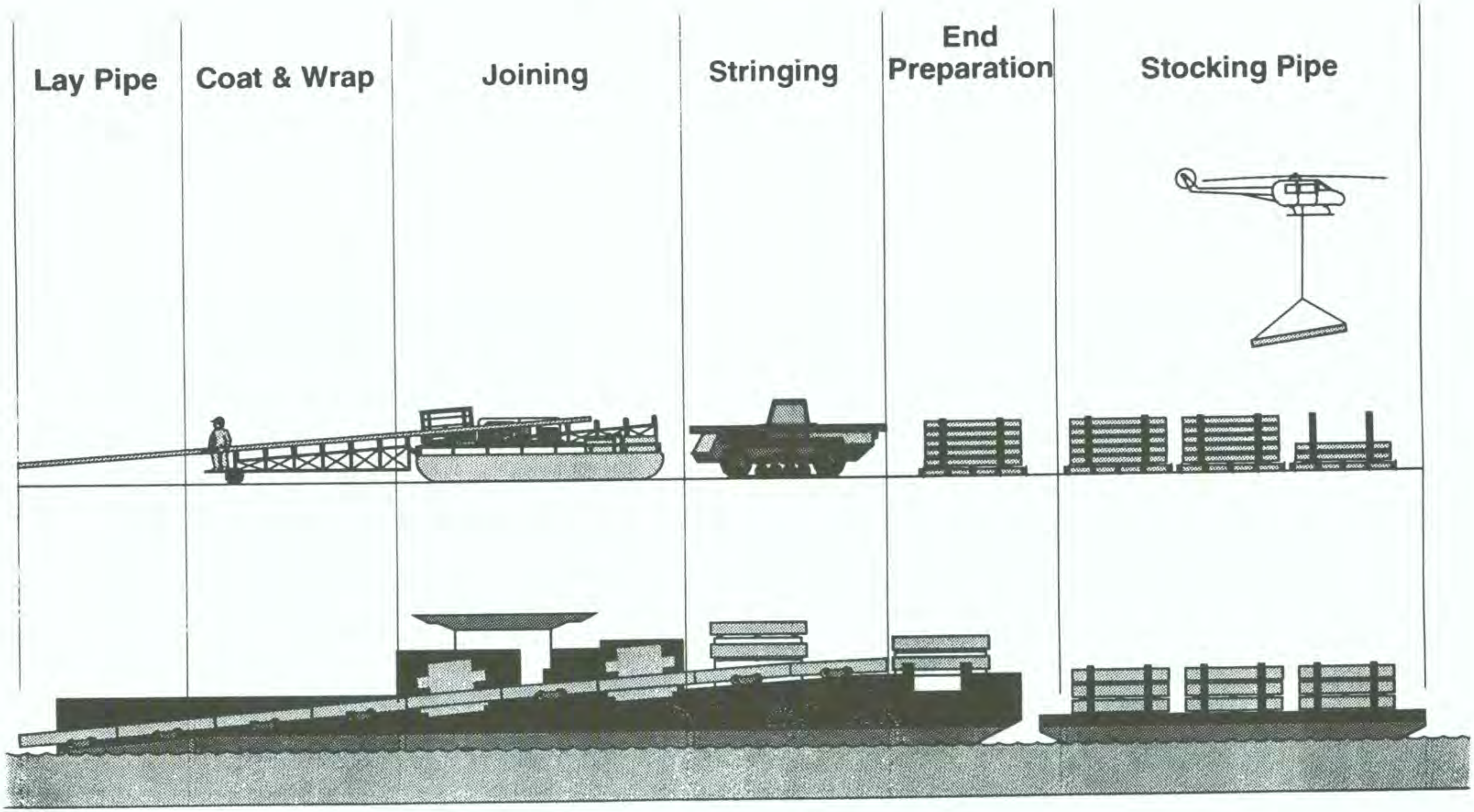
A. Conventional offshore oil development



B. Offshore development model applied to rain forest

Figure 5.

LAY TRAIN



PLSCENE1

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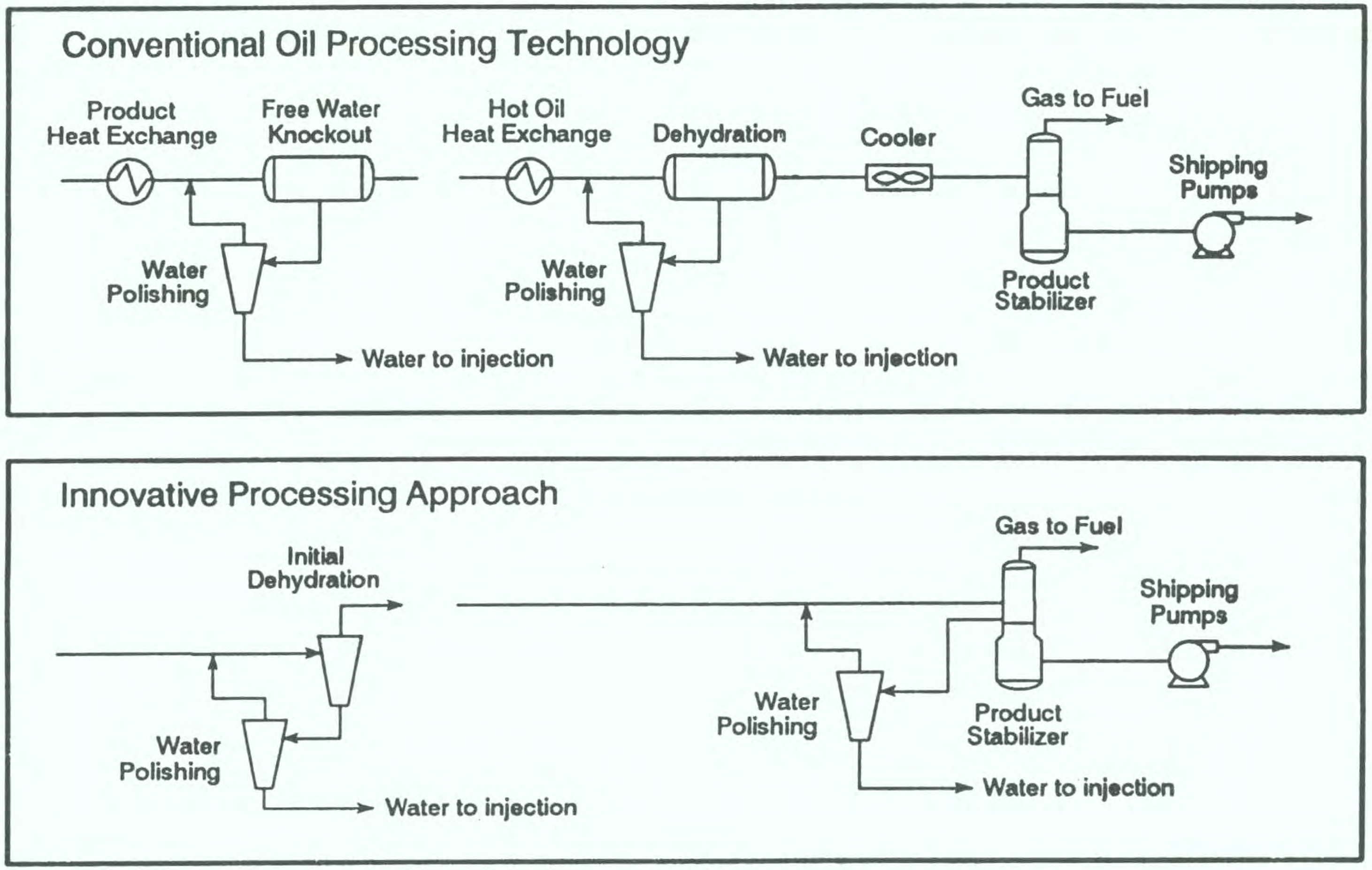

Figure 6. Conventional and alternate oil field technology

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