*INTEGRATION OF DESALINATION AND HYDROGEOLOGIC TECHNOLOGIES FOR INCORPORATION OF UNACCOUNTED FOR BRACKISH AND THERMAL GROUNDWATER IN LOCAL AND REGIONAL WATER BALANCE

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ABSTRACT

Traditional concepts of aquifers and watersheds do not link faulting and related fracture zones with country or regional water balances. This misperception of the interaction of local and regional surface and groundwater hydrologies has severely constrained growth planning in arid countries. It is becoming increasingly evident that a realistic depiction is a prerequisite for integrated resource management.

Recent advances in the technology of groundwater exploration have led to a revision of conventional definitions of aquifers and basin water balances, especially in arid regions. Modern, interdisciplinary teams of technologists and scientists, using space-age remote sensing combined with advanced geophysical, geological and geographic information system (GIS) mapping techniques are discovering accessible, useable fresh, brackish and hydrothermal groundwaters in regions where traditional methods failed to detect the resources.

At the same time, major progress in the development of low cost desalination technologies has opened the possibility that newly identified, naturally recharged reservoirs of brackish and thermal groundwater can be economically developed and treated for beneficial use.

State-of-the-art groundwater exploration and desalination technologies can now be fully integrated with socio-economic and environmental databases using GIS to map, test, develop and effectively manage multi-source water resources on a regional scale. This combination of space-age technologies offers an unprecedented opportunity for near-term economical development of significant quantities of renewable groundwater in arid areas.

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I. INTRODUCTION

1.1 The Water Balance - A Traditional Perspective

Water balance calculations form the basis for some guiding principles of regional and country water resources planning. The traditional definition of "water balance" is the quantity of renewable fresh water available for beneficial use from precipitation in an "average" year from a measured catchment area (surface and groundwater), such as a river basin. When more water is removed from the catchment area than is captured and recharged from precipitation, there is a deficit in the water balance. Conversely, when more water capture occurs than is withdrawn from a given catchment, a water surplus is assumed to exist.

Deep percolation is not measured and in arid countries is traditionally assumed to represent less than ten percent of precipitation when calculating the water balance [1]. Percolation into fractured bedrock is treated as a localized phenomenon with no impact on overall aquifer recharge, storage or regional transmission. The traditional definition of "watershed" is a topographically-controlled catchment area. Usually, available topographic maps or aerial photos are used to delineate the "watershed" and its geomorphic features. Rainfall volumes are calculated from captured quantities in different types of rain gauges at sparsely scattered meteorological stations, or extrapolated from experimental watersheds or catchment areas deemed to be similar by the investigator. Total recharge of soil moisture storage and groundwater is calculated from annual averages of rainfall versus evapotranspiration, plus a few measurements of water levels in observation wells and soil moisture monitoring stations.

The principal discharge from a watershed is assumed to be from surface runoff and evapotranspiration (E-T), with negligible amounts (less than ten percent) generally attributed to groundwater leakage. Runoff is estimated from what little available stream gauge data exists, while E-T calculations rely on a variety of experimental, but widely used formulae and empirical models, most of which require sizable amounts of data on temperature, humidity, wind speed, solar radiation, soils characteristics, vegetative cover and depth to water table [2]. Such data are not usually available, and resulting water balance calculations generally have a high degree of uncertainty.

Renewable groundwater within a watershed is traditionally considered to be the recharge of surface and near-surface aquifer systems which are mapped and characterized by hydrologists, while deeper groundwater is thought to be principally "fossil" waters, stored in porous sedimentary rocks with negligible potential for active natural recharge. It is traditionally assumed that any broadscale use of these aquifers would constitute "mining" the water [3]. Also, until recently, only fresh groundwaters were considered to represent a beneficial resource. This meant that underground brackish and saline waters were not recognized as a viable resource to be integrated into the water balance.

Until recent technologies made automated data recording and telemetering possible, sparse meteorological stations were necessarily located for the convenience of human observers. The base-line data from these stations represented an insignificant portion of the aerial extent of the landscape and was not representative of water dynamics in large basins [4].

This paucity of critical hydrometeorological and hydrogeological data has led water scientists, engineers and politicians to focus large-scale water studies and development almost exclusively on surface "watersheds". Meanwhile, poorly understood groundwater resources are usually developed through independent wildcat drilling, involving very little "before-the-fact" exploration science or follow-up monitoring. Water wells contribute significant quantities of fresh water to beneficial use. For example, approximately 50 percent of the drinking water in the USA is supplied from groundwater [5]. Nevertheless, due to the lack of mandatory industry standards for the methods used to locate, drill, log and monitor water wells, these millions of boreholes have added very little but confusion to the body of knowledge about the resource.

In the few cases, where "exceptionally" high-yield wells intercept productive geologic formations by chance, hydrologists have sought to evaluate these resources by applying conventional approaches, resulting in decades of academic debate without scientific verification. The ensuing data-short decisions can have profound consequences, such as potential overuse and harming of a renewable resource, exemplified by the debate over Libya's Kufra and Sarir Basins [6,7,8], or non-use with potential political strife and human suffering, as demonstrated by the debate over development of deep aquifers in Egypt's western desert [9].

1.2 Water Balance - The Space Age Perspective

The scientific community is in general agreement that more data must be acquired to improve calculations of water balances, especially in arid zones, such as the Mid-East. Furthermore, recent advances in technology are making new methodology available for use in characterization of groundwater resources associated with fault and fracture zones [10,11,12]. Modern programs of exploration are being proposed to map and model such resources in regions with chronic water scarcities like the Levant [13,14]. However, past attempts to accurately map these complex aquifers with traditional hydrogeologic concepts and methods have failed. This is in part due to severe baseline data constraints of localized studies, which cover only a few square kilometers of regional phenomena, rather than the thousands of square kilometers essential for integration of information from complex landscapes.

The advent of the space age introduced innovative methodologies in the fields of remote-sensing, geophysics, geology and computer-based Geographic Information Systems (GIS), which permitted simultaneous integration of multiple databases. The most immediate, non-government beneficiaries of these modern tools and concepts were the oil, gas and economic minerals exploration industries, which were able to dramatically, and cost-effectively accelerate their discovery process.

Coincidentally, the water drilling industry was designing and building modified oil rigs for deep, hardrock water well drilling, unfortunately without capturing the opportunity for scientific application of such technologies to true water exploration.

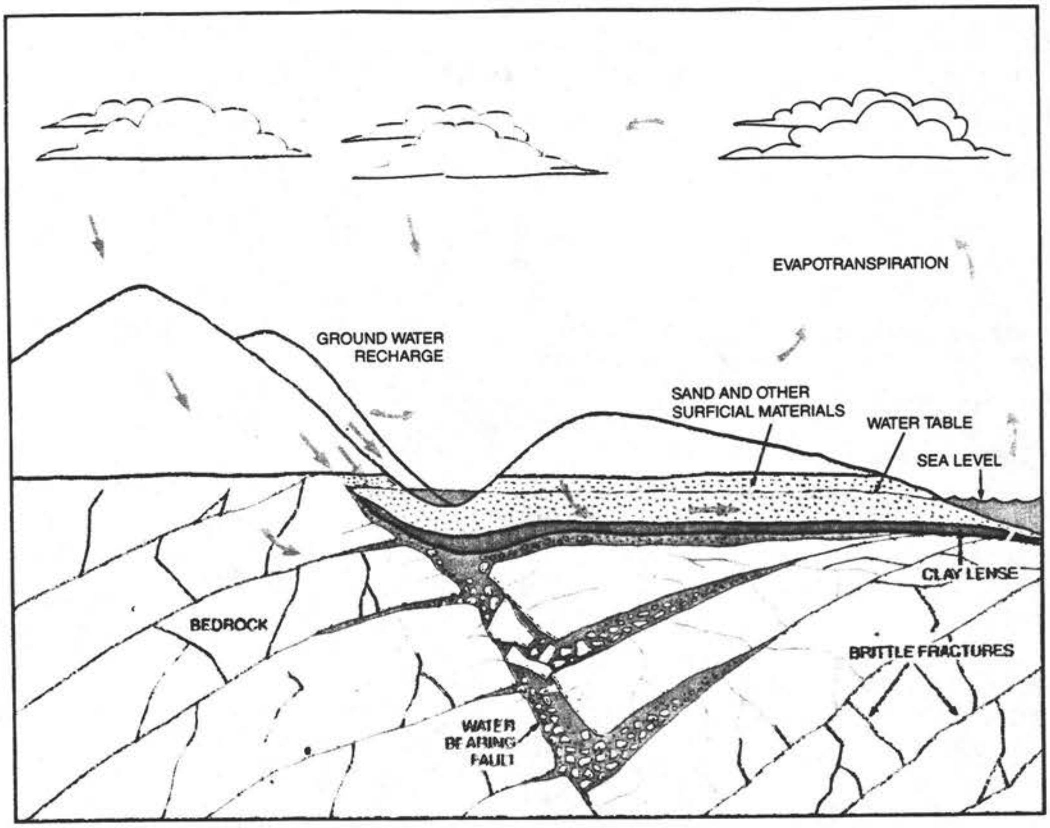
At the same time, university and government research scientists, carrying out studies related to defense and hazardous and nuclear waste site evaluations, contributed valuable data on hydraulic conductivities and the architecture of fracture systems in certain massive, crystalline rock formations [15].

These innovations, complimented by modern, expanded information management and computation capabilities, marked the onset of discoveries by an interdisciplinary team of groundwater exploration scientists, who re-examined and updated traditional hydrogeological concepts by integrating new space-age technologies with *a priori* databases to re-define the perception of "watershed" in more realistic terms (figure 1a & 1b).

II. FROM WATERSHED TO MEGAWATERSHED

The "Megawatershed" is a new paradigm of groundwater occurrence, resulting from the first practical application of a modern, integrated exploration process to groundwater mapping, which recognized the critical importance of tectonically-induced regional fracture permeability in the hydraulics and hydrology of a watershed, and the related promise of vast, untapped and renewable fresh and brackish water resources throughout the arid world.

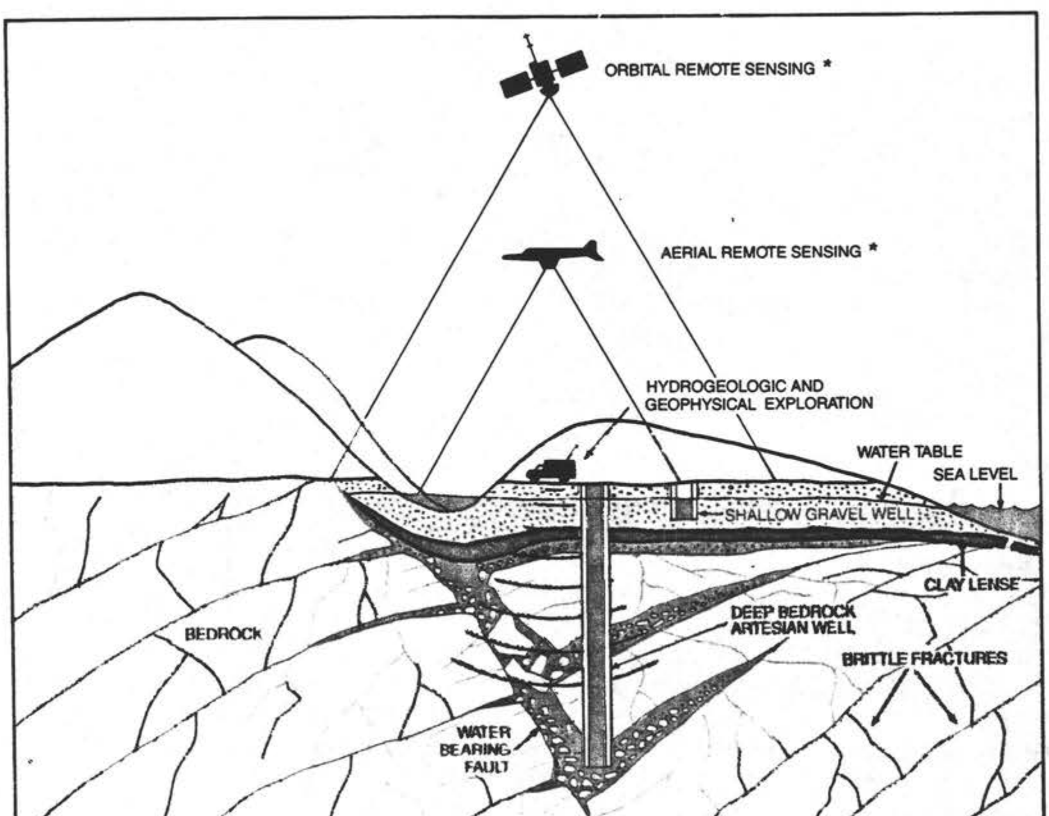
The term "Megawatershed" describes the broadest possible three dimensional catchment area and transmitter of water, originating from multiple recharge zones, and with surface and subsurface flow strongly controlled by regional fault and fracture zones in the bedrock. Some of the fracture systems act as continuous zones of secondary permeability, through which large amounts of water may flow (Figure 2). In such cases, "Mega" refers to order-of-magnitude effects on groundwater flow in tectonically-derived fracture systems, which considerably extend traditional bounds of basin catchment, as well as enhance groundwater recharge and



THE HYDROLOGIC CYCLE

Rainwater falls on rock and soil. Some of the water evaporates and the remaining water infiltrates into the shallow surficial materials and deep into fractured bedrock systems. The water then flows under pressure through these various materials toward the seas or into desert basins. Some of the water escapes into surface streams and springs, while much water is lost to subsurface evaporation under hot desert basins. Vast quantities of groundwater in some regions flow into the sea, rising as submarine springs or discharging into offshore sediments, all eventually evaporating, completing the cycle.

figure 1a



SPACE AGE TECHNOLOGY

Earth Water Technology's specialized, proven groundwater exploration program includes advanced remote sensing, geological, geophysical and hydrological mapping and interpretive techniques. Screened and evaluated databases are processed digitally and presented to clients in GIS format, with hard copy, compatible disc backup and training.

figure 1b

evaporation. The specialized methodology which discovered the megawatershed phenomenon is now being employed to map, develop and manage these untapped resources.

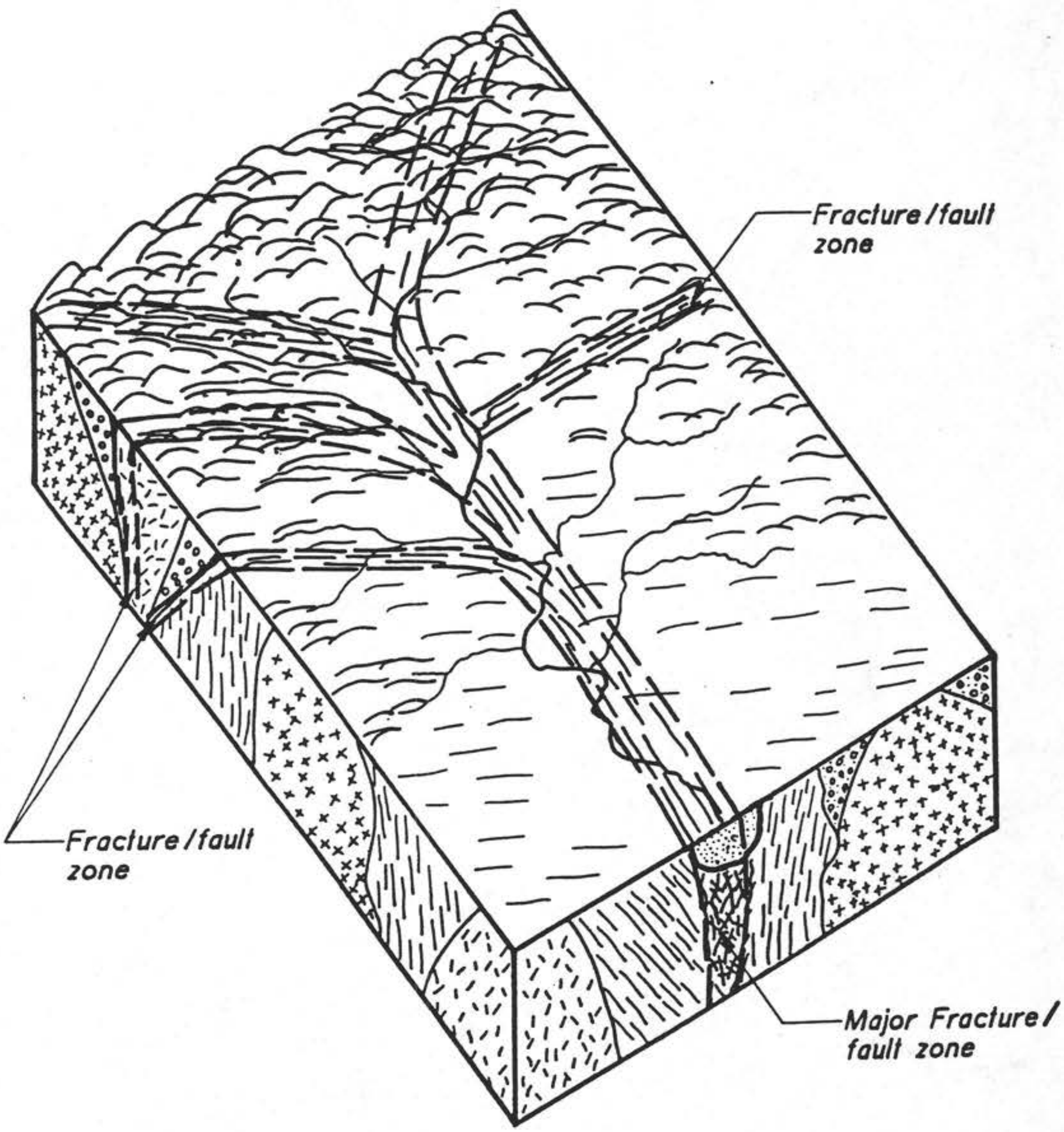
2.1 Global and Regional Occurrence

Extensive megawatershed systems are found worldwide; from the Pampa del Tamarugal Basin of Northern Chile (Margaritz et al, 1990), to the Great Artesian Basin of Australia, to the Nubian Sandstone Aquifers of Northern Africa and the Levant. Aquifers in these regions derive their characteristics from the interaction of climatic and hydrometeorological conditions with the regional geology. The premise of the megawatershed paradigm is that the aquifers under these enormous basins possess not only simple primary porosity/permeability, but also pervasive secondary permeability. This fracture permeability adds a major new dimension of catchment, renewable flow and storage in currently recognized aquifers, and at the same time defines new aquifers in previously discounted non-porous rocks (figure 3).

These megawatershed attributes have been observed over the centuries, but could not be fully understood without the visual and objective evidence made possible by modern technology. Formal studies of groundwater relationships to bedrock fractures date back at least to 1835, when W. Hopkins [16] listed his observation of rectangular arrangements in topographic features, faults, mineralized veins, joints and alignment of springs. At the onset of the space-age, Professor Angellilo [17] of the California Institute of Technology, graphically described a stress-field induced and fractured-rock controlled basin recharge and discharge system in his regional analysis of the Mohave River basin groundwater regime. Results of independent research carried out in East Africa from 1984 - 1989 by Bisson et al, showed that the effects of tectonic controls on hydraulic conductivity are related to regional groundwater flows through fractured rock (figure 4). A conceptual model of the Megawatershed Phenomenon was presented by Bisson and El-Baz [18,19].

2.2 The Megawatershed Exploration Technology

The Megawatershed Exploration Program[c] was developed over a period of 15 years by the scientists who originally recognized megawatersheds as a discreet hydrogeological phenomenon. This team of scientists founded EarthWater Technology International (ETI) to apply their unique experience, learning curve and technology to megawatershed development in the arid world. The team uses its scientific approach to groundwater exploration, incorporating a variety of tools and techniques adapted from recent advances in multi-disciplinary technology. The exploration program represents highly specialized technologies which have proven successful in the U.S., the Middle East and Africa. The methodology uses a hierarchical, cost-effective process in selection and



Schematic Illustration of the Control of Drainage by Major Fault/Fracture Zone.

figure 2

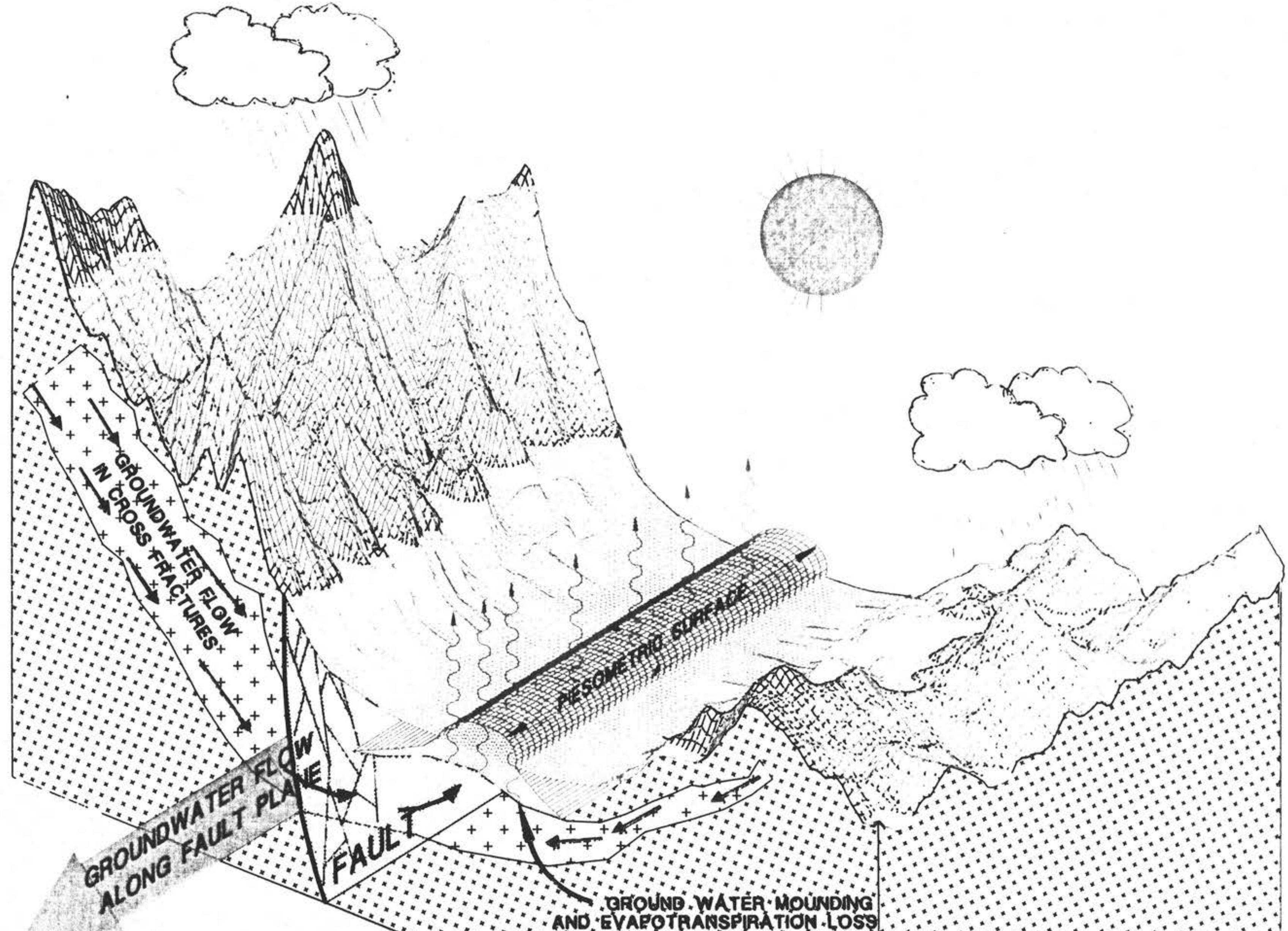
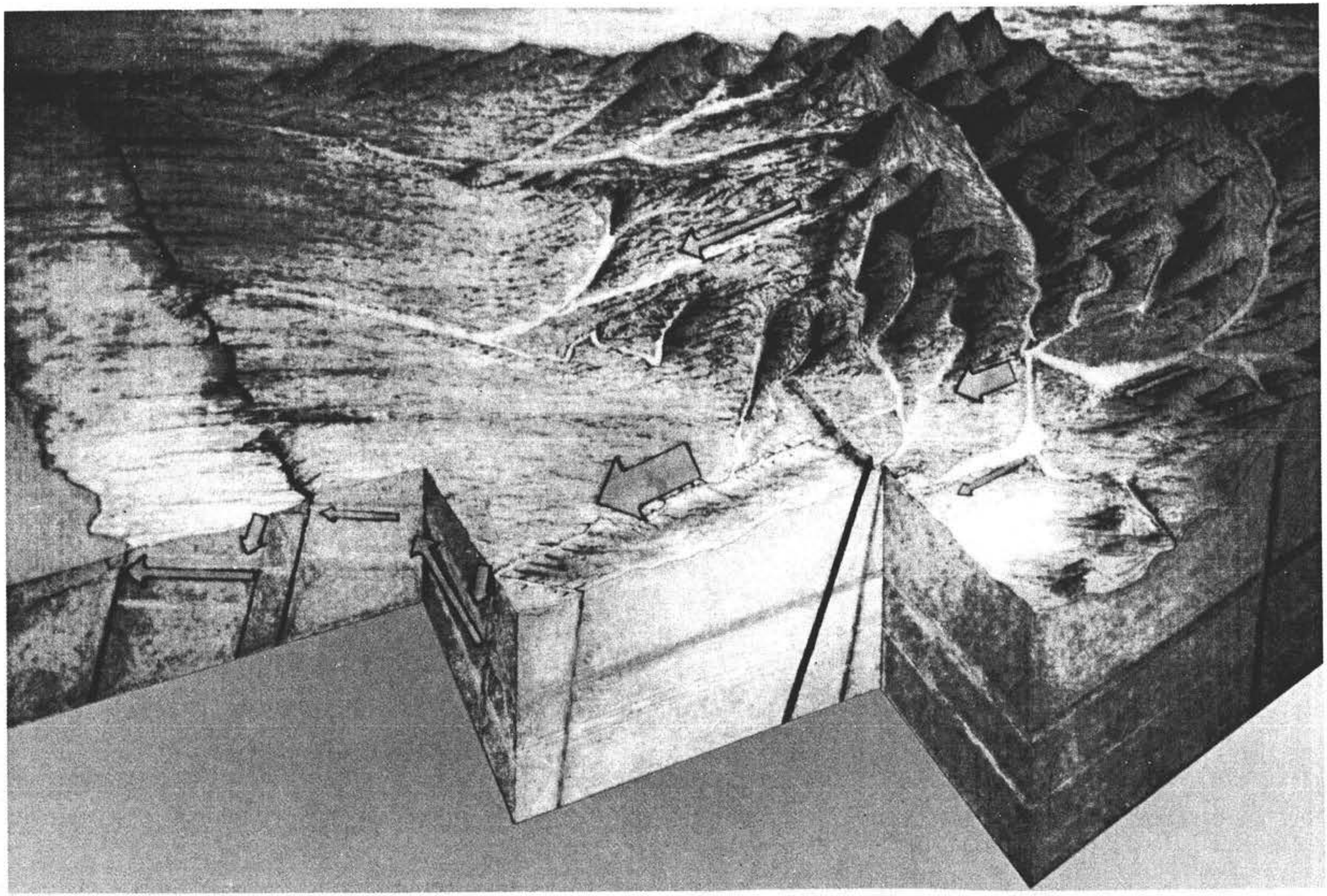


figure 3

ANATOMY OF A MEGAWATERSHED

Bedrock aquifers are replenished by rain and snow in highland regions, which infiltrate into fracture zones and flow along fractures toward the seas and inland basins. Large quantities of these groundwater resources are discharged from beneath the seas and from solar-deflated water tables in desert basins. Throughgoing fault and fracture systems also hydraulically connect basins to one another over thousands of square kilometers.



. Perspective Illustration of the Megawatershed Model Applied in the Red Sea Province of Sudan. Arrows Illustrate Mountain Recharge to Fracture Systems and Alluvial Storage.

figure 4

classification of favorable target areas, according to complexities and the likelihood of quantity, quality, origin and renewability of water reserves. Client selected target areas are further evaluated for economic advantages of exploitation and expected treatment requirements.

2.3 Components of the Megawatershed Exploration Program[c]

The team's exploration program includes efficient collection, evaluation and qualified use of all available groundtruth and existing baseline data, irrespective of quality and fragmentation. The method requires extensive use of digital remote-sensing and GIS databases, plus custom-designed field mapping, specialized geophysical well siting (figure 1b), strict specifications and control of the drilling process, concluding with a GIS-based, integrated megawatershed management and training program for water resource managers (figure 5).

2.3.1 Remote Sensing and GIS

ETI begins its search for identification of megawatersheds from the global perspectives of space at its fully integrated computer facility at EarthSatellite Corporation (EarthSat). Highly sophisticated satellite systems developed by the United States, Russia, France, Japan, and India provide multiband, multisource, global digital data that is required for the delineation of megawatersheds.

Proprietary computer algorithms and techniques are used to uniquely enhance the digital data and define areas in precise land-use terms, mapping soils, vegetation, and other baseline data concurrent with geological and hydrological attributes such as lithology, structural geology, drainage, erosional surfaces and soil moisture. EarthSat's Cropcast[c] system provides the team access to NOAA weather satellites and generates forecasts of worldwide precipitation. Historical satellite and climatological data going back as far as the turn of the century can also be accessed to provide estimates of temporal and spacial distributions.

Additionally, the team incorporates high altitude aircraft and ground based analyses to cross check and corroborate the computer analysis throughout the exploration program. Map-accurate satellite images are generated, permitting the team to work with planimetrically correct, high resolution color prints of entire countries or regions. In addition to EarthSat's state-of-the-art image processing facility, its high-volume photo-lab facilities are capable of printing on-line, color composite images up to 1.27m x 2.5 m in size from the project's remote sensing and GIS databases. The team is able to work efficiently from both on-line computer terminals and hard copy image maps, an absolute requirement for the fast-track, highly integrated Megawatershed

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GIS - BRIDGE

THE CONNECTION FROM REMOTELY SENSED DATA TO GIS INFORMATION

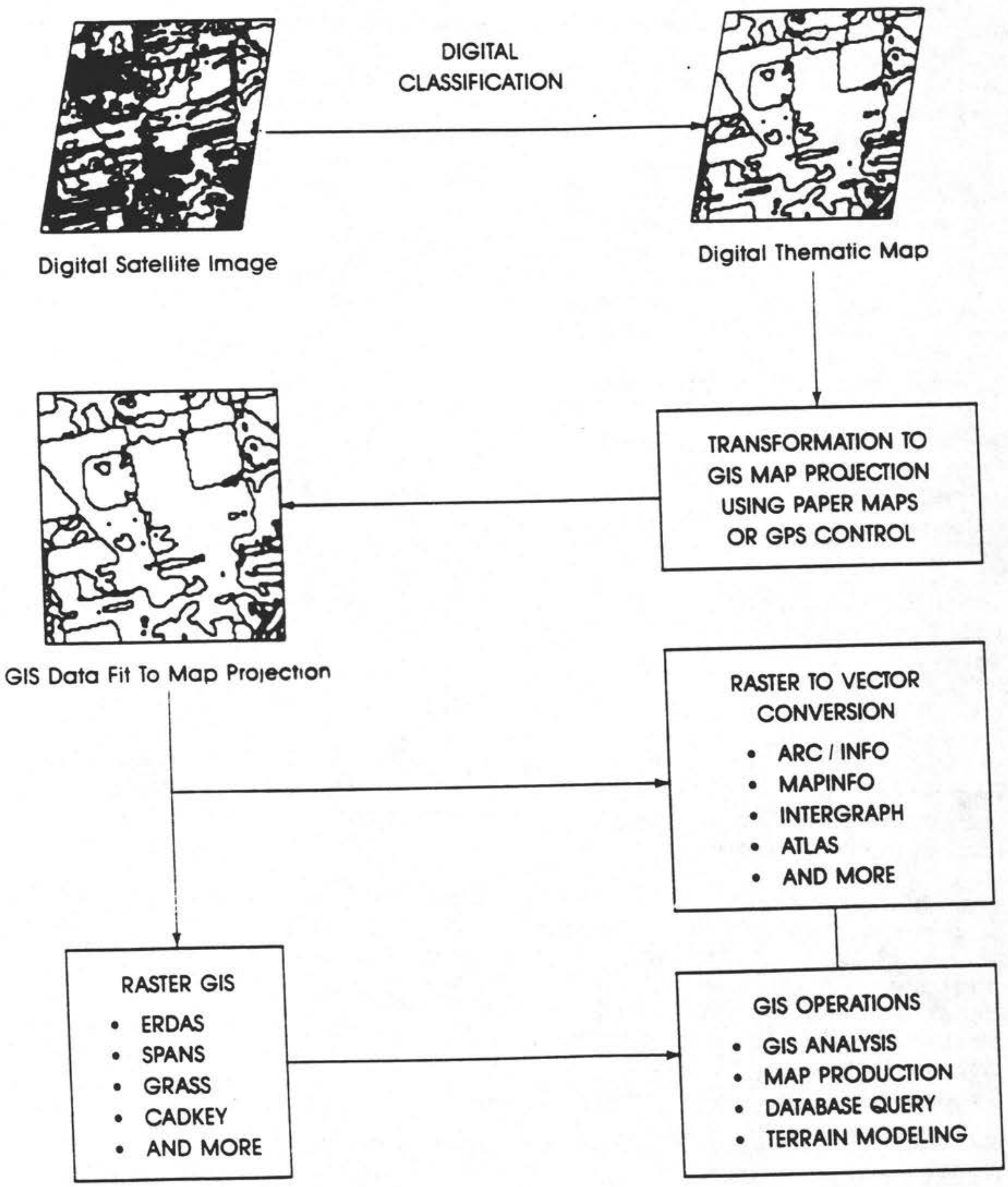


figure 5

Exploration Program[c], which was adapted from years of experience with water, mineral, oil and gas exploration.

All data from the remote sensing analysis is digitally logged into an ARC-Info Geographic Information System (GIS), along with published (and unpublished) maps, borehole logs, water yields and quality, site-specific data from geophysical and geological reports and other information relevant to the water exploration, well testing and development process. The GIS is integrated into EarthSat's 100 gigabyte computer facility and utilizes several large format digitizing tables and Sun 4 work stations, which allows effective integration and continuous cross-correlation of the enormous amounts of complex data sets required for large-area Megawatershed Exploration Programs. In addition to digital tape generation for team and client use, in-house, 42 inch color plotters expedite the necessary process of producing working maps for closely scheduled field work and team/client interaction, as well as final map products.

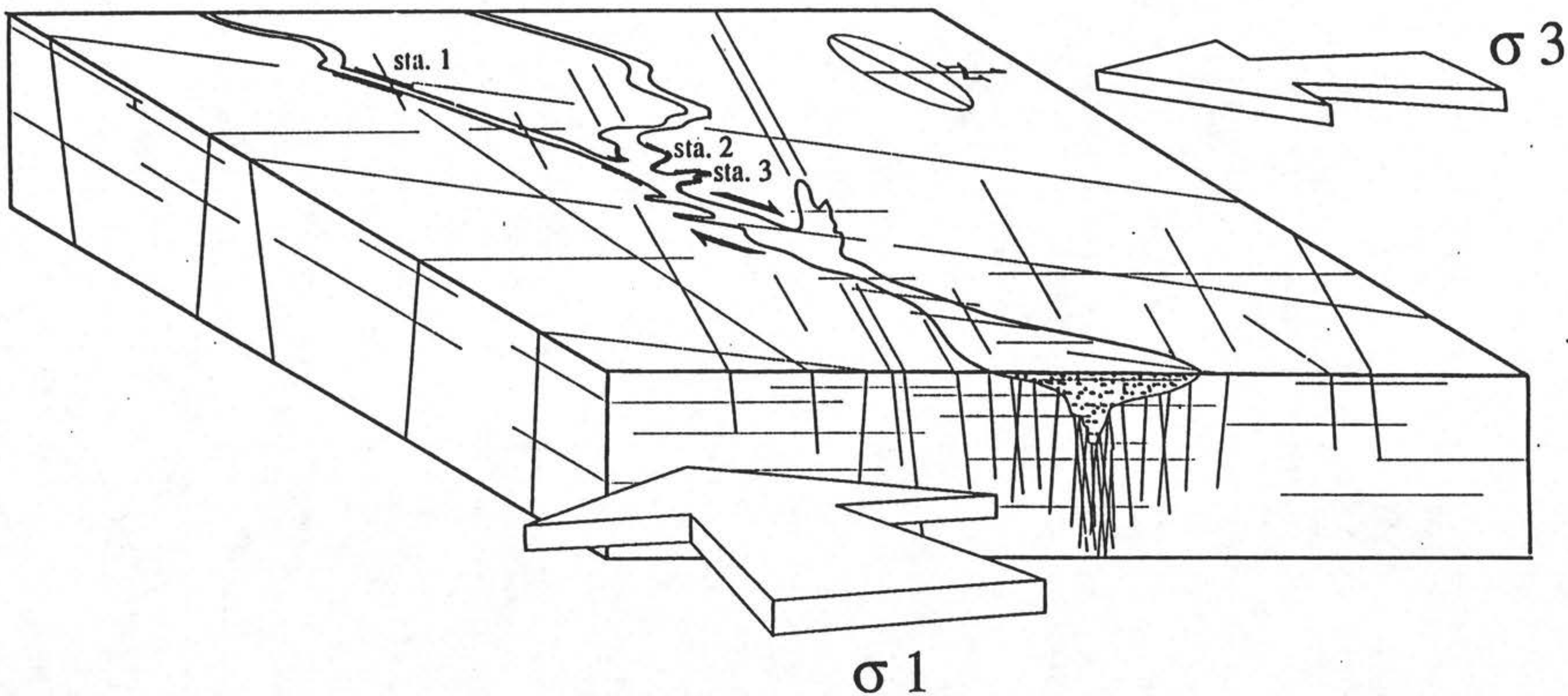
2.3.2 **Geotectonic Mapping**

Geotectonics is a branch of geology dealing with the broad architecture of the Earth's crust, including the major structural or deformational features, such as folds, faults and fractures, as well as their interrelationships, origins, and historical evolution [20]. Such geotectonic processes create regional open fracturing of the Earth's crust and form permeable and hydraulically conductive environments. Over geologic time, as precipitation infiltrates into these extensive three-dimensional fracture networks, megawatersheds evolve.

By 1978, the ETI team members had discovered that a thorough understanding of the tectonic history and related fracture fabric of a region is the starting point and the benchmark for megawatershed exploration, against which all geomorphological, stratigraphic, geochemical, hydrological, and other analytical outputs are measured.

The basic scientific, intellectual and physical tools used to interpret geotectonic regimes include tectonic models, published scientific reports and maps about the target areas and other regions worldwide. The team uses a correlative system for processing tectonic models integrally with the inter-active features of the remote-sensing/GIS data for identification and documentation of unique characteristic features of the megawatershed (figure 6).

In addition to standard, satellite MSS data, available airborne and orbital geophysical data, such as gravity, radiometry and radar from government and private overflights are included in the final regional analysis.



This block diagram depicts the fault zone underlying Khor Quwab. The orientation of the fracture sets are mimic actual fracture set orientations. Sigma 1, the maximum compressive stress axis, and sigma 3 the minimum compressive stress axis, were derived using a grid search computer progıan from fault data collected in the area. The configuration of this tensor is compatible with a Miocene Red Sea rift phase stress configuration. Note the inferred right lateral motion on the fault zone. Three brittle fracture stations were placed within the fault zone and khor.

figure 6 - Tectonic Model, Red Sea Province, Sudan

2.3.3 Geophysical Methods

From simple electrical resistivity sensors to gravity meter, seismometers and electromagnetic sensors, earth scientists have for centuries invented, experimented with, improved upon and broadened the use of an amazing assortment of geophysical devices, in search of "non-invasive" ways to map the earth's subsurface. The complex physical and chemical nature of underground structures continues to challenge the most sophisticated geophysical instruments.

Through 15 years of field testing the team has developed a proprietary, systematic approach to geophysical testing of megawatershed attributes. It uses numerous experimentally derived and tested geophysical equipment and data interpretive techniques for regional resource evaluation and well-field targeting. All interpretive data is digitized into the GIS for integrated analyses with other data sets during the exploration process.

III. INTEGRATED MEGAWATERSHED MANAGEMENT

Hydrologists and water resources management specialists have endeavored for many decades to resolve the uncertainties associated with the interaction and continuity of surface and groundwater, as conventionally defined within the "watershed" and "aquifer" systems. Surface water continuity often visibly extends across international boundaries, creating added complexities to the search for interstate compacts. Groundwater resource continuity, however, remains a mystery, impeding diplomatic solutions which require technical certainties for consensus building.

Within states, large portions of the total groundwater resource remain unknown due to technological constraints, or are disregarded if they are saline, brackish or thermal. The megawatershed concept is the integrator of space-aged technologies and modern water resources management methods. The results provide a practical method of regional groundwater assessment and classification with respect to quantity, quality and sustainability. Implicit in the program is an estimation of renewable, fresh, hydrothermal, brackish and saline groundwater reserves for integrated development by many countries with chronic water scarcities.

Advances in desalination technologies must consider this new dimension for expanding water resources of countries worldwide and target special studies of new hybrid treatment systems, combined with megawatershed exploration programs, to reduce the cost of fresh water production. Such integrated programs must also be supported by substantive research which target choices and efficiency of appropriate desalination packages.

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