Total Petroleum Systems of the Trias/Ghadames Province, Algeria, Tunisia, and Libya—The Tanezzuft-Oued Mya, Tanezzuft-Melrhir, and Tanezzuft-Ghadames

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Foreword

This report was prepared as part of the U.S. Geological Survey World Petroleum Assessment 2000. The primary objective of World Petroleum Assessment 2000 is to assess the quantities of conventional oil, gas, and natural gas liquids outside the United States that have the potential to be added to reserves in the next 30 years. Parts of these assessed volumes reside in undiscovered fields whose sizes exceed the stated minimum-field-size cutoff value for the assessment unit, which is variable but must be at least 1 million barrels of oil equivalent. Another part of these assessed volumes occurs as reserve growth of fields already discovered. However, the contribution from reserve growth of discovered fields to resources is not covered for the areas treated in this report.

In order to organize, evaluate, and delineate areas to assess, the Assessment Methodology Team of World Petroleum Assessment 2000 developed a hierarchical scheme of geographic and geologic units. This scheme consists of regions, geologic provinces, total petroleum systems, and assessment units. For World Petroleum Assessment 2000, regions serve as organizational units and geologic provinces are used as prioritization tools. Assessment of undiscovered resources was done at the level of the total petroleum system or assessment unit.

The world was divided into 8 regions and 937 geologic provinces. These provinces have been ranked according to the discovered known oil and gas volumes (Klett and others, 1997). Then, 76 "priority" provinces (exclusive of the United States and chosen for their high ranking) and 26 "boutique" provinces (exclusive of the United States) were selected for appraisal of oil and gas resources. Boutique provinces were chosen for their anticipated petroleum richness or special regional economic or strategic importance.

A geologic province is an area having characteristic dimensions of hundreds of kilometers that encompasses a natural geologic entity (for example, a sedimentary basin, thrust belt, or accreted terrane) or some combination of contiguous geologic entities. Each geologic province is a spatial entity with common geologic attributes. Province boundaries were drawn as logically as possible along natural geologic boundaries, although in some places they were located arbitrarily (for example, along specific water-depth contours in the open oceans).

Total petroleum systems and assessment units were delineated for each geologic province considered for assessment. It is not necessary for the boundaries of total petroleum systems and assessment units to be entirely contained within a geologic province. Particular emphasis is placed on the similarities of *petroleum fluids* within total petroleum systems, unlike geologic provinces and plays in which similarities of *rocks* are emphasized.

The total petroleum system includes all genetically related petroleum that occurs in shows and accumulations (discovered and undiscovered) generated by a pod or by closely related pods of mature source rock. Total petroleum systems exist within a limited mappable geologic space, together with the essential mappable geologic elements (source, reservoir, seal, and overburden rocks). These essential geologic elements control the fundamental processes of generation, expulsion, migration, entrapment, and preservation of petroleum within the total petroleum system.

An assessment unit is a mappable part of a total petroleum system in which discovered and undiscovered oil and gas fields constitute a single relatively homogeneous population such that the methodology of resource assessment based on estimation of the number and sizes of undiscovered fields is applicable. A total petroleum system might equate to a single assessment unit. If necessary, a total petroleum system may be subdivided into two or more assessment units such that each assessment unit is *sufficiently* homogeneous in terms of geology, exploration considerations, and risk to assess individually. Differences in the distributions of accumulation density, trap styles, reservoirs, and exploration concepts within an assessment unit were recognized and *not* assumed to extend homogeneously across an entire assessment unit.

A numeric code identifies each region, province, total petroleum system, and assessment unit. The criteria for assigning codes are uniform throughout the project and throughout all publications of the project. The numeric codes used in this study are:

Unit	Name	Code
Region	Middle East and North Africa	**2**
Province	Trias/Ghadames	2**054**
Total Petroleum Systems	Tanezzuft-Oued Mya	2054**01**
	Tanezzuft-Melrhir	2054**02**
	Tanezzuft-Ghadames	2054**03**
Assessment Units	Tanezzuft-Oued Mya Structural/Stratigraphic	205401**01**
	Tanezzuft-Melrhir Structural/Stratigraphic	205402**01**
	Tanezzuft-Ghadames Structural/Stratigraphic	205403**01**

A graphical depiction that places the elements of the total petroleum system into the context of geologic time is provided in the form of an events chart. Items on the events chart include (1) the major rock-unit names; (2) the temporal extent of source-rock deposition, reservoir-rock deposition, seal-rock deposition, overburden-rock deposition, trap formation, generation-migration-accumulation of petroleum, and preservation of petroleum; and (3) the critical moment, which is defined as the time that best depicts the generation-migration-accumulation of hydrocarbons in a petroleum system (Magoon and Dow, 1994). The events chart serves only as a timeline and does not necessarily represent spatial relations.

Probabilities of occurrence of adequate charge, rocks, and timing were assigned to each assessment unit. Additionally, an access probability was assigned for necessary petroleum-related activity within the assessment unit. All four probabilities, or risking elements, are similar in application and address the question of whether at least one undiscovered field of minimum size has the potential to be added to reserves in the next 30 years somewhere in the assessment unit. Each risking element thus applies to the entire assessment unit and does not equate to the percentage of the assessment unit that might be unfavorable in terms of charge, rocks, timing, or access.

Estimated total recoverable oil and gas volumes (cumulative production plus remaining reserves, called "known" volumes hereafter) quoted in this report are derived from Petroconsultants, Inc., 1996 Petroleum Exploration and Production database (Petroconsultants, 1996a). To address the fact that increases in reported known volumes through time are commonly observed, the U.S. Geological Survey (Schmoker and Crovelli, 1998) and the Minerals Management Service (Lore and others, 1996) created a set of analytical "growth" functions that are used to estimate future reserve growth (called "grown" volumes hereafter). The set of functions was originally created for geologic regions of the United States, but it is assumed that these regions can serve as analogs for the world. This study applied the Federal offshore Gulf of Mexico growth function (developed by the U.S. Minerals Management Service) to known oil and gas volumes, which in turn were plotted to aid in estimating undiscovered petroleum volumes. These estimates of undiscovered petroleum volumes therefore take into account reserve growth of fields yet to be discovered.

Estimates of the minimum, median, and maximum number, sizes, and coproduct ratios of undiscovered fields were made based on geologic knowledge of the assessment unit, exploration and discovery history, analogs, and, if available, prospect maps. Probabilistic distributions were applied to these estimates and combined by Monte Carlo simulation to calculate undiscovered resources.

Illustrations in this report that show boundaries of the total petroleum systems, assessment units, and extent of source rocks were compiled using geographic information system (GIS) software. The political boundaries shown are not politically definitive and are displayed for general reference only. Oil and gas field center points were provided by, and reproduced with permission from, Petroconsultants (1996a and 1996b).

Abstract

Undiscovered conventional oil and gas resources were assessed within total petroleum systems of the Trias/Ghadames Province (2054) as part of the U.S. Geological Survey World Petroleum Assessment 2000. The Trias/Ghadames Province is in eastern Algeria, southern Tunisia, and westernmost Libya. The province and its total petroleum systems generally coincide with the Triassic Basin. The province includes the Oued Mya Basin, Melrhir Basin, and Ghadames (Berkine) Basin. Although several total petroleum systems may exist within each of these basins, only three "composite" total petroleum systems were identified. Each total petroleum system occurs in a separate basin, and each comprises a single assessment unit.

The main source rocks are the Silurian Tanezzuft Formation (or lateral equivalents) and Middle to Upper Devonian mudstone. Maturation history and the major migration pathways from source to reservoir are unique to each basin. The total petroleum systems were named after the oldest major source rock and the basin in which it resides.

The estimated means of the undiscovered conventional petroleum volumes in total petroleum systems of the Trias/Ghadames Province are as follows:

[MMBO, million barrels of oil; BCFG, billion cubic feet of gas; MMBNGL, million barrels of natural gas liquids]

Total Petroleum System	MMBO	BCFG	MMBNGL
Tanezzuft-Oued Mya	830	2,341	110
Tanezzuft-Melrhir	1,875	4,887	269
Tanezzuft-Ghadames	4,461	12,035	908

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Introduction

Undiscovered conventional oil and gas resources were assessed within total petroleum systems of the Trias/Ghadames Province (2054) as part of the U.S. Geological Survey (USGS) World Petroleum Assessment 2000. This study documents the geology, undiscovered oil and gas volumes, exploration activity, and discovery history of the Trias/Ghadames Province.

The Trias/Ghadames Province is a geologic province delineated by the USGS; it is located in eastern Algeria, southern Tunisia, and westernmost Libya (fig. 1). The province area encompasses approximately 390,000 km^2 (square kilometers) and generally coincides with the Triassic Basin. It contains the Melrhir, the Ghadames or Berkine (called Ghadames (Berkine) hereafter), and part of the Oued Mya Basins. Neighboring geologic provinces, delineated by the USGS, include the Pelagian Basin (2048), Hamra Basin (2047), Illizi Basin (2056), Grand Erg/Ahnet Basin (2058), and Atlas Uplift (2053).

More than one total petroleum system may exist within each of the basins in the Trias/Ghadames Province (Boote and others, 1998). Data available for this study are insufficient to adequately determine the relative contribution of each total

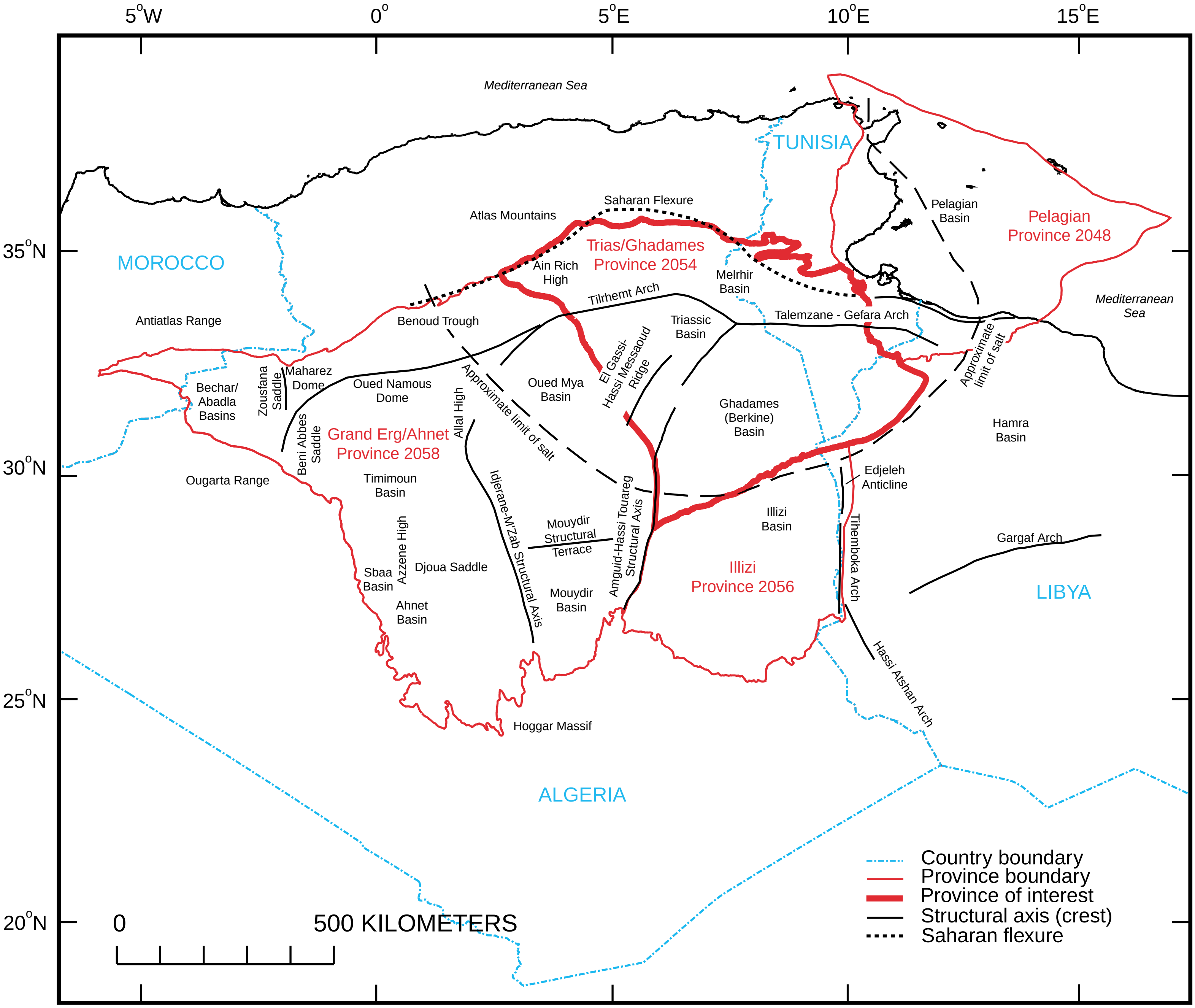


Figure 1 . North-central Africa, showing USGS-defined geologic provinces and major structures (modified from Aliev and others, 1971; Burollet and others, 1978; Montgomery, 1994; Petroconsultants, 1996b; Persits and others, 1997).

petroleum system to individual accumulations and therefore preclude further subdivision. Consequently only “composite” total petroleum systems are described in this report, each of which contains one or multiple total petroleum systems. These composite total petroleum systems are called the Tanezzuft-Oued Mya, Tanezzuft-Melrhir, and Tanezzuft-Ghadames Total Petroleum Systems (fig. 2). The Tanezzuft-Melrhir and Tanezzuft-Ghadames Total Petroleum Systems are located almost entirely within the Trias/Ghadames Province. The Tanezzuft-Oued Mya Total Petroleum System extends into the neighboring Grand Erg/Ahnet Province. Tanezzuft refers to the Silurian Tanezzuft Formation, which is the oldest major source rock in the total petroleum system; in the total petroleum system name, “Tanezzuft” is then followed by the basin name in which the total petroleum system exists. Due to scarcity of data, province and total petroleum system boundaries can only be approximately delineated and therefore are subject to future modification.

One assessment unit was defined for each total petroleum system; the assessment units coincide with the total petroleum systems (fig. 3). The assessment units are named after the total petroleum system with a suffix of “Structural/Stratigraphic.” This suffix refers to the progression from a structural and combination trap exploration strategy to a stratigraphic (subtle) trap exploration strategy.

The Trias/Ghadames Province contains more than 16,000 million barrels (MMB) of known (estimated total recoverable, that is, cumulative production plus remaining reserves) petroleum liquids (approximately 15,000 million barrels of oil, MMBO, and 1,000 million barrels of natural gas liquids, MMBNGL) and approximately 25,000 billion cubic feet of known natural gas (10^9 CFG or BCFG) (Petroconsultants, 1996a). The Trias/Ghadames Province contains the giant Hassi Messaoud oil field, in the Tanezzuft-Oued Mya Total Petroleum System.

Province Geology

The southern and southwestern boundaries of the Trias/Ghadames Province represent the approximate extent of Triassic and Jurassic evaporites that were deposited within the Mesozoic-aged Triassic Basin. The neighboring Hamra Basin is somewhat continuous with the Ghadames (Berkine) Basin, but was separated for this study.

A T-shaped anticlinorium, the major structural feature within the Trias/Ghadames Province, divides the province into the three total petroleum systems (figs.1 and 2). It consists of truncated Paleozoic structures beneath a major unconformity (the Hercynian unconformity). The anticlinorium can be observed on pre-Hercynian unconformity subcrop maps and is delineated by the absence of middle and upper Paleozoic rocks. A west-to-east- trending arch is located in the northern part of the province and consists of the Tilrhemt and the Talemzane-Gefara Arches. A southwest-to-northeast-trending structure called the Amguid-Hassi Touareg structural axis intersects the west-to-east-trending Tilrhemt and Talemzane-Gefara Arches (van de Weerd and Ware, 1994). The Amguid-Hassi Touareg structural axis is a system of faults and large horst structures (Aliev and others, 1971). This fault system deviates eastward into the Ghadames (Berkine) Basin, south of the Talemzane-Gefara Arch. A secondary structure called the El Gass-Hassi Messaoud Ridge lies parallel to part of the Amguid-Hassi Touareg structural axis.

The Tanezzuft-Oued Mya Total Petroleum System coincides with the Oued Mya Basin and is bounded on the north by the Tilrhemt Arch, on the east by the Amguid-Hassi Touareg structural axis, on the south by the Mouydir Structural Terrace, and on the west by the Idjerane-M'Zab structural axis. Most of the Oued Mya Basin lies within the Grand Erg/Ahnet Province, west of the Amguid-Hassi Touareg structural axis. However, most of the oil and gas accumulations in this basin had been discovered in the crux of the two westernmost “legs” of the T-shaped anticlinorium (figs. 1 and 2), which had been assigned to the Trias/Ghadames Province. The Mouydir Structural Terrace is a break or hingeline in the slope of the basement rocks that separates the Oued Mya Basin from the perched Mouydir Basin.

The Tanezzuft-Melrhir Total Petroleum System coincides with the Melrhir Basin (or Trough), bounded on the north by the Saharan Flexure, and on the south by the Tilrhemt and Talemzane-Gefara Arches (figs. 1 and 2). The Melrhir Basin is a shallow foredeep.

The Tanezzuft-Ghadames Total Petroleum System coincides with the Ghadames (Berkine) Basin and is bounded on the north by the Talemzane-Gefara Arch, on the east by the Hamra Basin, on the south by the Illizi Basin, and on the west by the Amguid-Hassi Touareg structural axis. The boundary between the Ghadames (Berkine) and the Illizi Basins is delineated by a break or hingeline in the slope of the basement. This hingeline was responsible for separating much of the petroleum generation, migration, and accumulation between two basins (fig. 4*A*). The eastern and southern boundaries approximate the extent of the superimposed Triassic Basin.

A portion of another total petroleum system within Cretaceous rocks is present in the Trias/Ghadames Province. It is an extension of a total petroleum system from within the Atlas Uplift Province (2053) to the north. This total petroleum system includes three fields located near the northern province boundary close to the Saharan Flexure but is not described in this study.

Tectonic History

The regional stratigraphy is continuous across North Africa, but petroleum generation, migration, and entrapment within each total petroleum system have been controlled by the tectonic history of individual basins. Deformational events in the region, most of them minor, are recorded by unconformities reflecting basin tilting, uplift, and erosion of intracratonic structural axes at various times throughout the Phanerozoic. The main structural axes are shown in figures 1 and 4. The main deformational events occurred in the Precambrian to Early Cambrian (Pan African event), Late Silurian to Early Devonian, Late Devonian (Frasnian event), Carboniferous to Permian (Hercynian event), Early Jurassic, Early Cretaceous (Aptian, Austrian event), Late Cretaceous, and Tertiary (Eocene to Oligocene, Pyrenean event) (Aliev and others, 1971; Peterson, 1985; Boudjema, 1987; van de Weerd and Ware, 1994).

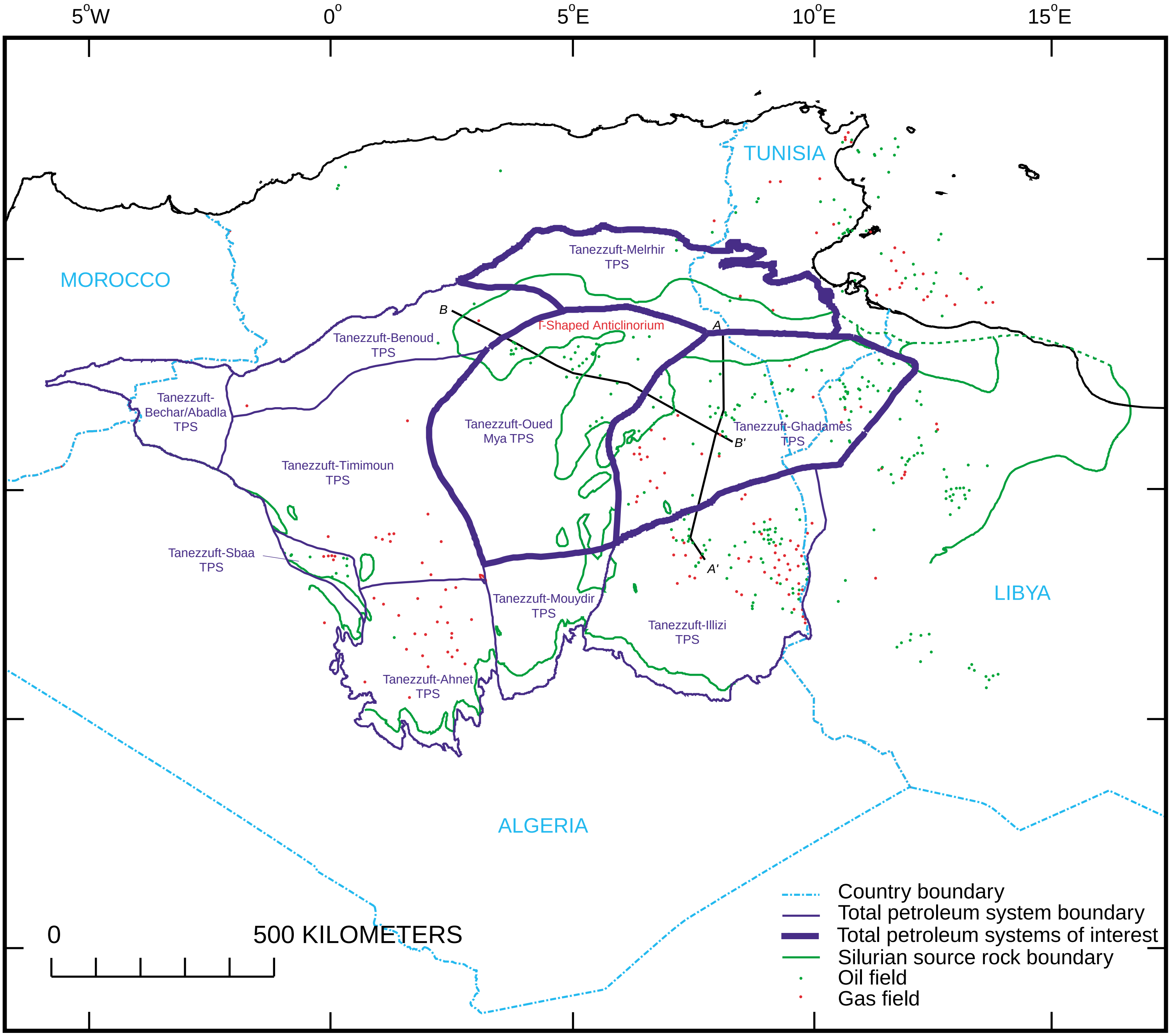


Figure 2. North-central Africa, showing the areal extent of total petroleum systems and Silurian source rocks (Tanezzuft Formation), and locations of stratigraphic cross sections (modified from Petroconsultants, 1996b; Persits and others, 1997; Boote and others, 1998).

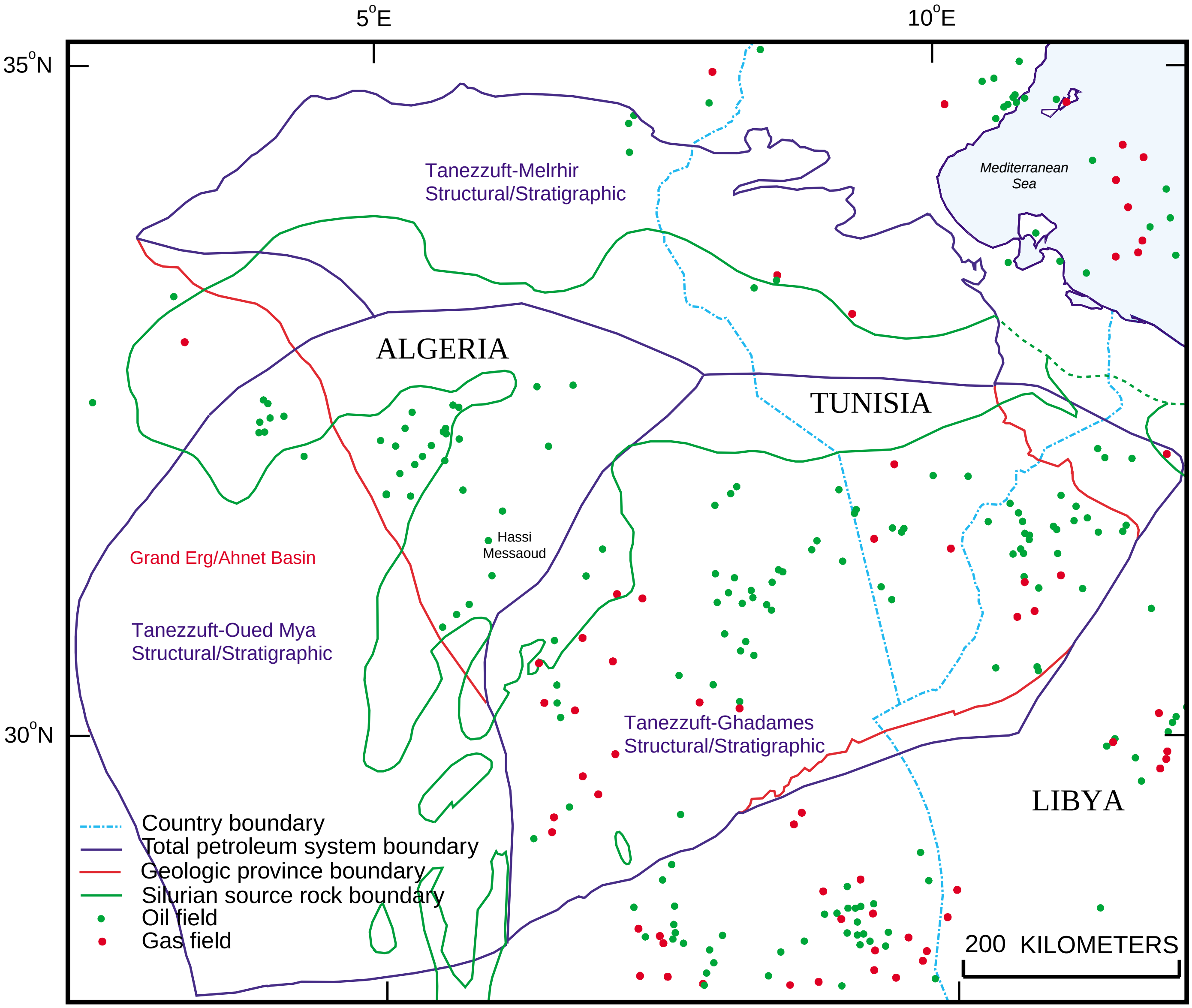
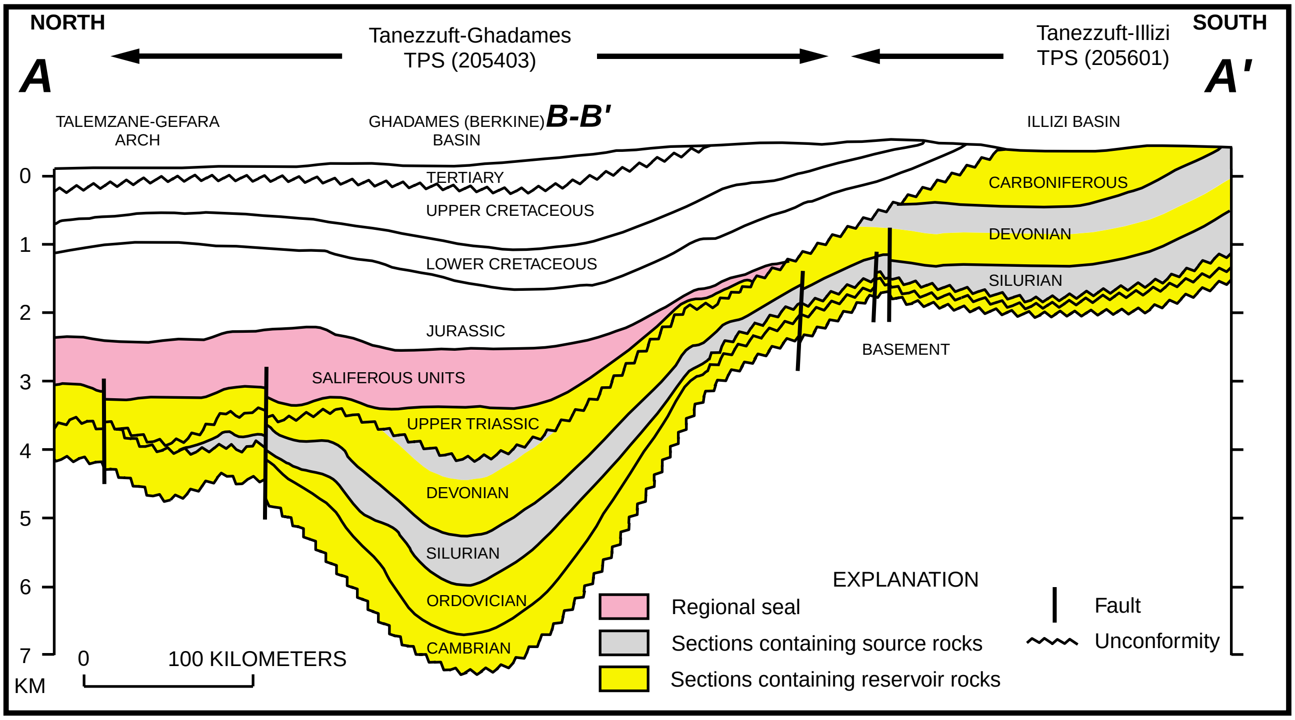
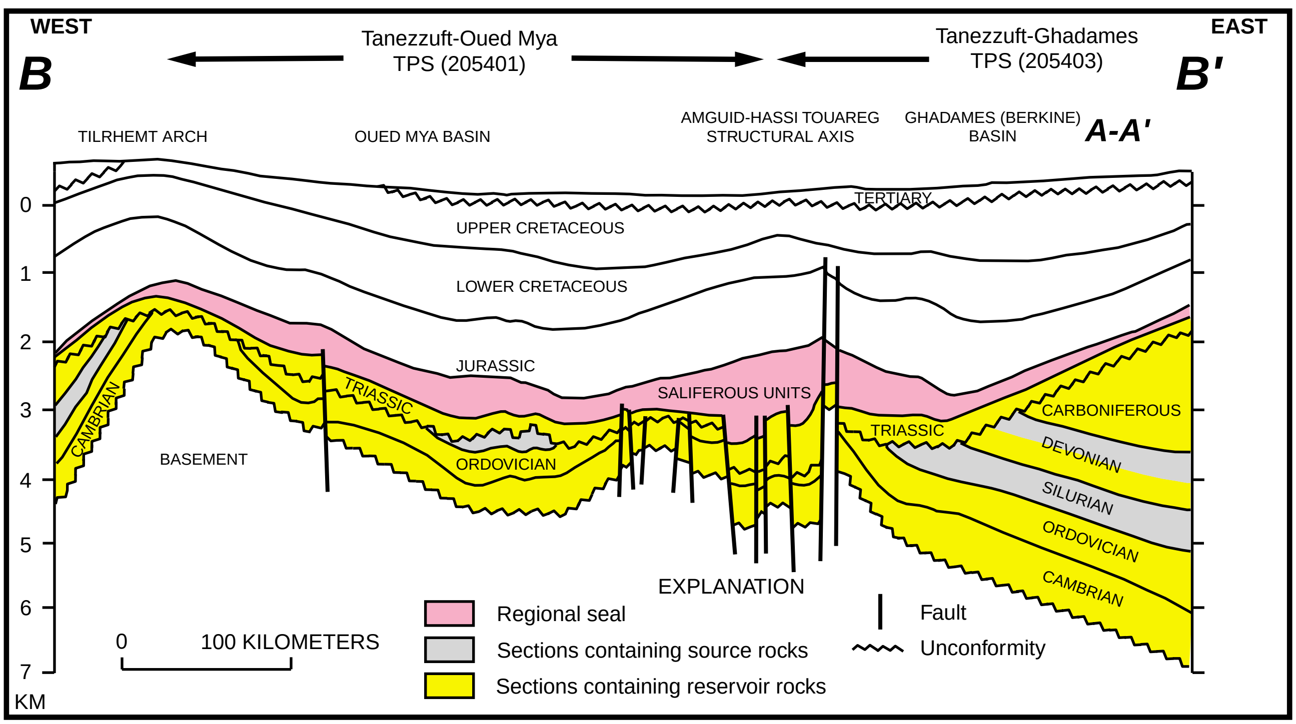


Figure 3. Areal extent of assessment units within the Trias/Ghadames Province (modified from Petroconsultants, 1996b; Persits and others, 1997).



A

Figure 4. Stratigraphic cross sections through Trias/Ghadames and Illizi Provinces. *A*, North-to-south stratigraphic cross section through the Ghadames (Berkine) and Illizi Basins (modified from van de Weerd and Ware, 1994, after Aliev and others, 1971).



B

Figure 4—Continued. Stratigraphic cross sections. *B*, West-to-east stratigraphic cross section through the Oued Mya and Ghadames (Berkine) Basins (modified from van de Weerd and Ware, 1994, after Aliev and others, 1971).

Throughout most of the Paleozoic, North Africa was a single depositional basin on the northern shelf of the African craton (Aliev and others, 1971; van de Weerd and Ware, 1994). The basin generally deepened northward where deposition and marine influence were greater (Daniels and Emme, 1995). Some gentle but large structures existed in this area throughout the Paleozoic and affected the thickness of the sedimentary cover (Aliev and others, 1971; van de Weerd and Ware, 1994). There was a general conformity of structure throughout most of the Paleozoic until the Hercynian event. In the Late Silurian and Early Devonian, Laurasia separated from Gondwana resulting in minor deformation, uplift, and local erosion (Aliev and others, 1971; Boote and others, 1998). Many of the basins and uplifts preserved today were initially developed during this event from earlier structures (Peterson, 1985). Later, in the Middle to Late Devonian, the initial collision of Laurasia and Gondwana began resulting in erosion and further modification of preexisting structures (Boote and others, 1998).

Minor deformation occurred in the Late Silurian through the Devonian, resulting in uplift and local erosion (Aliev and others, 1971; van de Weerd and Ware, 1994; Boote and others, 1998). Within the Trias/Ghadames Province, uplift and erosion occurred on and near the Amguid-Hassi Touareg structural axis.

The Hercynian event marks the collision between Laurasia and Gondwana and caused regional uplift, folding, and erosion (Aliev and others, 1971; Boote and others, 1998). Paleozoic basins that were delineated by earlier tectonic events were modified, resulting in the development of several intracratonic sag and foreland basins (Aliev and others, 1971; van de Weerd and Ware, 1994; Boote and others, 1998). Structures that constitute the T- shaped anticlinorium were truncated.

Several transgressive-regressive cycles occurrred throughout the Paleozoic. Two major flooding events, one in the Silurian and the other in the Late Devonian, were responsible for the deposition of source rocks (Aliev and others, 1971; Boudjema, 1987). Many of the prograding fluvial, estuarine, deltaic, and shallow marine sands that were deposited during these cycles are now reservoirs (Aliev and others, 1971).

Petroleum was generated during the Carboniferous Period within deeper portions of the basins, but uplift caused generation to cease (Tissot and others, 1973; Daniels and Emme, 1995; Makhous and others, 1997). Subsequent erosion may have removed or dispersed petroleum that had accumulated in some areas (Boote and others, 1998).

During the early Mesozoic, extensional movements caused by the opening of the Tethys and Atlantic oceans developed a cratonic sag basin called the Triassic Basin. The depocenter was superimposed on some of the Paleozoic basins (Aliev and others, 1971; Boudjema, 1987). Triassic fluvial sands followed by a thick Triassic to Jurassic evaporite section were deposited within the sag basin (Aliev and others, 1971; Boudjema, 1987). Sandstones resulting from the fluvial deposition are major reservoirs, and the evaporites provide a regional seal for these fluvial reservoirs as well as Paleozoic reservoirs (Aliev and others, 1971). Clastic then carbonate deposition occurred throughout the remainder of the Mesozoic over much of the area (Aliev and others, 1971; Boudjema, 1987). Sediment deposition gradually diminished in the Tertiary (Aliev and others, 1971; Peterson, 1985; Boudjema, 1987).

Transpressional movements (wrenching) during Austrian deformation reactivated older structures such as those along the Amguid-Hassi Touareg structural axis, causing local uplift and erosion (Claret and Tempere, 1967; Aliev and others, 1971). Uplift of the Amguid-Hassi Touareg structural axis as well as the Tilrhemt and Talemzane-Gefara Arches of the T-shaped anticlinorium further separated the three total petroleum systems within the Trias/Ghadames Province.

The initial stages of the Africa-Arabia and Eurasia collision during Late Cretaceous to middle Tertiary caused compressional movements and uplift (Peterson, 1985; Guiraud, 1998).

These movements tilted the Triassic Basin to its present configuration (Aliev and others, 1971; Boote and others, 1998). Basins that existed where the present-day Atlas Mountains exist were inverted (Aliev and others, 1971). Inversion and tilting resulted in the development of the shallow Melrhir and Benoud foreland basins (Boote and others, 1998).

Petroleum was generated within the Triassic Basin depocenter throughout the Late Cretaceous and early Tertiary, but some spillage or secondary migration subsequently occurred (Boote and others, 1998; van de Weerd and Ware, 1994). Many structural traps formed by vertical movements of the basement during Mesozoic and Tertiary deformational events (Echikh, 1998).

Stratigraphy

The regional stratigraphy of lower Paleozoic sections is generally continuous, but the Devonian and overlying sections show more localized depositional systems. Stratigraphic nomenclature varies among the Saharan basins and countries. This study primarily uses nomenclature given in Boudjema (1987), Montgomery (1993), and Echikh (1998). Columnar sections, stratigraphic nomenclature, and correlations are shown in figure 5.

Principal source rocks are the Silurian Tanezzuft Formation and Middle to Upper Devonian mudstone (Givetian to Famennian) (Tissot and others, 1973; Daniels and Emme, 1995). Other minor or relatively unimportant source rocks are also present but contributed significantly less petroleum than did the Silurian or Middle to Upper Devonian mudstone (Daniels and Emme, 1995; Boote and others, 1998). Reservoir rocks include sandstone of Cambrian-Ordovician, Silurian, Devonian, Carboniferous, and Triassic age. Triassic to Jurassic evaporites, mudstone, and

Figure 5 (next two pages). Columnar section and stratigraphic nomenclature for Illizi, Triassic, and Ghadames (Berkine) Basins (modified from Boudjema, 1987). Major reservoir rocks are shown in yellow, source rocks in gray, and seals in red.

System	Stage	Illizi Basin (van de Weerd and Ware, 1994)	Triassic Basin (Boudjema, 1987)	Ghadames (Berkine) and Hamra Basins (Montgomery, 1994; Echikh, 1998)	General lithology (Boudjema, 1987)	Description (Boudjema, 1987) *Hercynian Unconformity*
Carboniferous	Stephanian	F	Tiguentourine	Dembaba		Mudstone, limestone, and gypsum
	Westphalian		El Adeb Larache			Limestone, gypsum, and mudstone
	Namurian	E	Oubarakat	Assed Jeffar		Limestone and sandstone
		D	Assekaifaf			Limestone and sandstone with concretions
	Visean	C B	Issendjel	Mrar		Mudstone and sandstone
	Tournaisian	A	(Sbaa)			Limestone and mudstone
Devonian	Strunian	F2	Gara Mas Melouki	Tahara (Shatti)		Sandstone
	Famen. -Frasnian		Tin Meras	Aouinet Ouenine		Mudstone *Frasnian Unconformity*
	Givetian - Eifelian	F3				Sandstone
				Ouan Kasa		Mudstone and limestone
	Emsian	F4-5	Orsine			Mudstone and sandstone
	Siegenian - Gedinnian	F6	Hassi Tabankort	Tadrart		Sandstone *Late Silurian-Early Devonian Unconformity*
Silurian			Zone de Passage	Acacus		Sandstone and mudstone
		"Argileux"	Oued Imirhou	Tanezzuft		Black mudstone with graptolites
		Gara Louki	Gres de Remada			Sandstone
			Argile Microcgl.	Bir Tlacsin		Microconglomeratic mudstone *Glacial Unconformity*
Ordovician	Cardocian		Gres d'Oued Saret	Memouniat		Limestone, sandstone, and mudstone
	Llandeilian - Llanvirnian	Edjeleh	M'Kratta Complex: Argiles d'Azzel	Melez Chograne		Silty black mudstone
	Arenigian	Hamra	Gres de Ouargla	Haouaz		Sandstone
			Quartzites De Hamra			Sandstone
	Tremadocian	In Kraf	Gres d'El Atchane	Achebyat		Sandstone and mudstone
			Argile d'El Gassi			Mudstone
Cambrian-Ordovician			Zone des Alternances Ri			Sandstone and mudstone
Cambrian		Hassi Leila	Hassi Messaoud: Ro	Hassaouna and Mouridizie		Sandstone
			R2			
			R3			Sandstone and conglomerate *Pan-African Unconformity*
Infra-Cambrian			Socle	Infra Tassilian/ Mouriziḍie		Metamorphic and magmatic rocks

System	Stage	Illizi Basin (Chaouchi and others, 1998)	Triassic, Ghadames (Berkine), and Hamra Basins (Montgomery, 1994)	General lithology (Boudjema, 1987)	Description (Boudjema, 1987)
Neogene	Pliocene				Conglomerate
Neogene	Pliocene				Marl, gypsum, and sandstone
Neogene	Miocene				Gypsum, marl, limestone, sandstone, and conglomerate
Neogene	Oligocene				Sandstone and marl *Pyrenean Unconformity*
Paleog.	Eocene		Al Hamra Group		Limestone and marl
Paleog.	Paleocene		Al Hamra Group		Anhydrite, limestone, dolostone, marl, and mudstone
Cretaceous	Senonian	Calcaire Marnes Calcaire Argile Gypse	Al Hamra Group		Anhydrite, limestone, dolostone, marl, and mudstone
Cretaceous	Turonian	Serie D'In Akamil	Al Hamra Group		Limestone and dolostone
Cretaceous	Cenomanian	Serie D'In Akamil	Nefousa Group		Anhydrite, dolostone, and marl
Cretaceous	Albian	Serie de Taouratine	Nefousa Group		Sandstone, mudstone, and dolostone *Austrian Unconformity*
Cretaceous	Aptian	Serie de Taouratine	Nefousa Group		Sandstone, mudstone, and dolostone *Austrian Unconformity*
Cretaceous	Barremian	Serie de Taouratine	Continental Intercalaire		Sandstone and mudstone
Cretaceous	Neocomian	Serie de Taouratine	Cabao		Sandstone and dolomitic mudstone
Jurassic	Malm	Serie de Taouratine / Zarzaitine Superieur	Scesciuch (Shakshuk)		Anhydrite, limestone, dolostone, marl, and sandstone
Jurassic	Dogger	Zarzaitine Superieur	Tigi		Mudstone, sandstone, limestone, and anhydrite
Jurassic	Lias	Zarzaitine Superieur / Zarzaitine Moyen	Saliferous Units		Salt, anhydrite, and mudstone
Triassic		Zarzaitine Inferieur	Argilo-Greseux Superieur (Gassi Touil) Argilo-Carbonate (Oulad Nsir) Argilo-Greseux Inferieur (Nezla)		Sandstone, mudstone, salt, and volcanic rocks *Hercynian Unconformity*

carbonate rocks provide a regional seal for reservoirs. Other seal rocks include intraformational Paleozoic marine mudstone and Triassic volcanic rocks.

During the late Precambrian and Early Cambrian, erosion of a preexisting craton to the south occurred due to uplift during the Pan African deformational event. Eroded sediments were deposited northward as alluvial and fluvial deposits and make up the thick Cambrian sandstone of the Mourizidie and Hassaouna Formations. The Hassaouna Formation is laterally equivalent to the Hassi Messaoud and Hassi Leila Formations, which are major oil and gas reservoirs (van de Weerd and Ware, 1994, Petrocosultants, 1996a).

The Lower Ordovician Achebyat and Haouaz Formations unconformably overlie the Hassaouna Formation. The Achebyat Formation is laterally equivalent to Argile d'El Gassi and Gres d'El Atchane. The overlying Haouaz Formation is laterally equivalent to the Hamra Formation and Gres de Ouargla. The uppermost beds of the Hassi Messaoud and Hassi Leila Formations contain the marine trace fossil *Tigillites* (also called *Scolites*), which is characteristic of a change from fluvial to shallow marine deposition (van de Weerd and Ware, 1994). The Haouaz Formation contains quartz-rich sandstone and mudstone that were deposited in marine and marginal marine environments and are major oil and gas producing reservoirs (Montgomery, 1993; van de Weerd and Ware, 1994). The Argile d'El Gassi and equivalents may be locally minor source rocks (Makhous and others, 1997; Malla and others, 1997).

Above the Haouaz sandstone are Middle Ordovician marine mudstone and fine-grained sandstone of the Melez Chograne Formation. The Melez Chograne Formation is laterally equivalent to the Argiles d'Azzel and Bir Ben Tartar Formation sandstone. The Argiles d'Azzel and other mudstone equivalents may be locally minor source rocks (Makhous and others, 1997; Malla and others, 1997).

Upper Ordovician to Lower Silurian marine and glacial mudstone and fine-grained sandstone include the Memouniat Formation, the Gres de Remada, the Argile Microconglomerate, and the Gres d'Oued Saret. The Ordovician to Silurian M'Kratta Complex includes these rocks as well as the underlying Melez Chograne and Haouaz Formations.

Overlying the Ordovician sediments is the organic-rich, graptolitic, marine mudstone of the Silurian Tanezzuft Formation. The Tanezzuft Formation, a principal source rock, was deposited during a major regional flooding event and contains mostly sapropelic and mixed (type I and II) kerogen (Daniels and Emme, 1995; Makhous and others, 1997). The present-day total organic carbon (TOC) content ranges from about 2 percent to greater than 17 percent across the Ghadames (Berkine) Basin, but may be reduced by as much as one-half due to increased thermal maturity (Daniels and Emme, 1995). The TOC content is greatest at the base of the section (Daniels and Emme, 1995). The thickness of the Tanezzuft Formation before Hercynian erosion varies from about 200 m to greater than 550 m (Daniels and Emme, 1995). The thickness, richness, and kerogen type of this source rock are regionally variable and dependent on paleogeography (Daniels and Emme, 1995).

The Tanezzuft Formation grades upward into the Upper Silurian Zone de Passage, or its lateral equivalent, the Acacus Formation. These formations consist of sandstone and mudstone representing marine to marginal marine depositional environments. Erosion during Late Silurian to Early Devonian deformation truncated these rocks on surrounding arches. The Acacus sandstone is the predominant oil and gas reservoir in the Libyan and Tunisian portion of the province (Petroconsultants, 1996a), but it may be an important reservoir elsewhere in the province where it has not been removed by erosion.

Devonian rocks unconformably overlie the Upper Silurian sediments. Devonian rocks consist of interbedded marine and deltaic sandstone and mudstone. The Devonian section includes the Tadrart, Hassi Tabankort, Ouan Kasa Formation, Orsine, Aouinet Ouenine, Tin Meras, Gara Mas Melouki, and part of the Tahara Formations. Sandstone members are each given a code, F2 to F6, with F6 being the oldest and F2 the youngest (fig. 5). The F6 sandstone (Tadrart Formation) and the Ouan Kasa Formation are important oil and gas reservoirs (Petroconsultants, 1996a; van de Weerd and Ware, 1994).

Middle to Upper Devonian mudstone is another major source rock, particularly the Frasnian-aged mudstone, which is the richest in this interval (Daniels and Emme, 1995). This mudstone, like the Silurian Tanezzuft Formation, was deposited during a major regional flooding event and contains mostly sapropelic and mixed (type I and II) kerogen (Daniels and Emme, 1995; Makhous and others, 1997). The present-day TOC content generally ranges from about 2 to 4 percent but can be as much as 14 percent (Daniels and Emme, 1995). The thickness of Middle to Upper Devonian mudstone exceeds 800 m in the central Ghadames (Berkine) Basin (Daniels and Emme, 1995). Lower Devonian (Emsian) mudstone (laterally equivalent to the Ouan Kasa or Orsine Formation) may be a locally minor source rock (Makhous and others, 1997).

Caboniferous formations include part of the Tahara Formation, the Mrar Formation (laterally equivalent to the Issendjel and the lower part of the Assekaifaf Formations), Assed Jefar (laterally equivalent to the upper part of the Assekaifaf Formation and the Oubarakat Formation), and the Dembaba Formation (laterally equivalent to the El Adeb Larache and Tiguentourine Formations). The Lower to Middle Carboniferous rocks consist of cycles of limestone or mudstone, siltstone, sandstone, and conglomerate representing deltaic and shallow-marine deposition. Lower Carboniferous mudstone may be locally minor source rocks (Makhous and others, 1997). Middle to Upper Carboniferous rocks consist of limestones, marls, dolostones, and gypsiferous mudstone that were deposited in evaporitic shallow-marine and tidal environments. Hercynian deformation started in Late Carboniferous and lasted through Early Permian. Erosion during this event removed most of the Paleozoic section along structural highs.

Permian rocks are only present in the eastern portion of the province. These rocks include Lower Permian pelagic limestone and mudstone, and Upper Permian bioherms, carbonate, and clastic rocks (Rigo, 1995). The Upper Permian Bir Jaja mudstone serves as a seal where present (Boote and others, 1998). Due to the limited extent, Permian stratigraphy is not shown in figure 5.

Triassic rocks include a lower clastic unit (Middle to Upper Triassic) and an upper evaporite unit that grades into the

Jurassic section. The clastic unit is subdivided into the Trias Argilo-Greseux Inferieur (includes the Nezla Formation, Ouled Chebbi Formation, and Ras Hamia Formation, and Kirchaou Sandstone), Trias Argilo-Carbonate, and Trias Argilo-Greseux Superieur (includes the Gassi Touil Formation and Zarzaitine Sandstone). Sandstone within this clastic unit is a major oil and gas reservoir. The lowermost Triassic rocks were deposited as continental (fluvial) sandstone and mudstone (Boudjema, 1987; Echikh, 1998). Because these beds were deposited over a dissected erosional surface of the Hercynian unconformity, thickness is variable (Bishop, 1975). The lowermost beds, Trias Argilo-Greseux Inferieur, were deposited as transgressive fluvial sandstone (Ford and Scott, 1997). These lower beds grade upward into dolostone, dolomitic mudstone, and anhydrite beds of the Trias Argilo-Carbonate (Boudjema, 1987; Montgomery, 1993). Rocks of the Trias Argilo-Greseux Superieur consist of alluvial mudstone, siltstone, and fine- to medium-grained sandstone (Boudjema, 1987; Montgomery, 1993). The Triassic clastic interval is thickest to the northeast (approximately 500 m) and thins to the south and west (Bishop, 1975). This clastic interval may grade into Jurassic sandstone by backstepping along the southern margins of the Ghadames and Oued Mya Basins (Boote and others, 1998). Some volcanic rocks (spilite, basalt, and andesite) are present throughout the Triassic section (reaching 150 m in some places) (Hamouda, 1980; Boudjema, 1987).

Overlying the Triassic clastic unit is an Upper Triassic and Lower Jurassic cyclic sequence of interbedded salt, anhydrite, gypsum, dolostone, and mudstone, called the Saliferous Units (fig. 5) (Bishop, 1975). These rocks form a regional seal for many oil and gas reservoirs (van de Weerd and Ware, 1994). The sequence is thickest near the Saharan Flexure in the north and thins southward. The combined maximum thickness (Triassic and Jurassic sections) exceeds 2,000 m. The southern limit of these rocks roughly coincides with the Trias/Ghadames Province boundary (fig. 1).

Above the evaporite interval are Middle to Upper Jurassic clastic and carbonate rocks. Within the Trias/Ghadames Province, these rocks include the Tigi and Scesciuch Formations, which were deposited in a shallow-marine environment (Bishop, 1975; Montgomery, 1993).

Lower Cretaceous rocks are represented by nonmarine and paralic sandstone. Included in this interval are the Cabao Formation and Continental Intercalaire. The top of the Continental Intercalaire is marked by the Austrian unconformity (Aptian) (Boudjema, 1987; van de Weerd and Ware, 1994). A thin and uniform bed of dolostone was deposited during the transgression that followed the erosional event (Bishop, 1975). Continental and shallow-marine sandstone and mudstone (Albian) overlay the dolostone. Upper Cretaceous to lower Tertiary rocks are shallow-marine carbonate rocks and evaporites, which were deposited on a north-dipping ramp. This interval includes the Nefousa and Al Hamra Groups.

Much of the Upper Cretaceous to Oligocene section was eroded during Pyrenean deformation. Miocene to Pliocene nonmarine clastic rocks and gypsum, and Quaternary sediments represent the Cenozoic section.

Petroleum Occurrence

Most of the oil and gas fields found by the end of 1995 in the Trias/Ghadames Province are located on subtle, low-relief structures within the central and northeast portions of the Ghadames (Berkine) Basin; on low-relief structures along the flank of the Tilrhemt Arch in the Oued Mya Basin; and on high-relief structures along the Amguid-Hassi Touareg structural axis (fig. 1). Most of these accumulations are within anticlines, faulted anticlines, or fault blocks developed during Hercynian and Austrian deformation (Boote and others, 1998; Petroconsultants, 1996a). Accumulations in combination traps, those containing both structural and stratigraphic components, are common.

Regional Exploration History

Exploration activity was not consistent through time in Algeria, Tunisia, and Libya. Exploration activity in Algeria fluctuated due to its war for independence from 1954 to 1962, nationalization of the oil industry from 1963 to 1971, political and economic problems into the 1980’s, and more favorable contractual terms in the late 1980’s (Traut and others, 1998; Montgomery, 1994). Tunisia and Libya also experienced fluctuations and discontinuities in exploration activity. Between 1963 and the late 1980’s, both Algeria and Tunisia had legislation regarding concession contracts and royalties that discouraged exploration by foreign companies (Montgomery, 1994). Since the late 1980’s, however, Algeria and Tunisia revised their legislation, encouraging foreign companies to explore and develop oil and gas resources (Davies and Bel Haiza, 1990; SONATRACH, c. 1992; Montgomery, 1994; Traut and others, 1998).

Not all areas in Algeria, Tunisia, and Libya were accessible for exploration. Shifting sand of Saharan Africa deserts presents technical difficulties in exploration and hazards in production operations (Echikh, 1998). Since the 1980’s, some of these technical difficulties in exploration have been resolved. Recent advances in gathering, processing, and reprocessing of seismic data allow exploration beneath sand-sea environments such as the Algerian Grand Erg Oriental where the Ghadames (Berkine) and Illizi Basins lie (van de Weerd and Ware, 1994; Macgregor, 1998).

New discoveries can be easily brought on line without construction of major pipelines because a basic infrastructure has been established (SONATRACH, c. 1992). Algeria has an extensive pipeline network that connects most of the major producing areas to port cities in Algeria and Tunisia (Pennwell, 1996). The pipelines allow transportation of oil, gas, and natural gas liquids. In Libya, an oil pipeline connects fields of the Ghadames (Berkine) and Hamra Basins to the port city of Az Zawiyah. An extension of this pipeline was completed in 1996 that connects producing areas within the Murzuk Basin with the coast (Traut and others, 1998; Pennwell, 1996), and another pipeline is planned to connect the Libyan portion of the Trias/Ghadames Province to the coast (Arab Petroleum Research Center, 1996).

The Tanezzuft-Oued Mya Total Petroleum System (205401)

The Tanezzuft-Oued Mya Total Petroleum System is an important total petroleum system with respect to known oil volumes, containing about 70 percent of the discovered oil in the province. This total petroleum system extends into the neighboring Grand Erg/Ahnet Province (figs. 1 and 2). An events chart (fig. 6) summarizes the timing of sources, reservoirs, seals, trap development, and generation and migration of petroleum. Table 1 shows the formation names, ages, and lithology for abbreviations used in the events chart.

Source Rocks

The principal source rock in the Tanezzuft-Oued Mya Total Petroleum System is the Silurian Tanezzuft Formation (or lateral equivalents) (Boote and others, 1998). Middle to Upper Devonian mudstone may provide another source of petroleum but is not present over most of the basin (Makhous and others, 1997; Boote and others, 1998). Devonian source rocks were truncated by erosion during Hercynian deformation and are present only in the southwestern part of the total petroleum system.

In the Oued Mya Basin, the present-day TOC content of Silurian (and Lower Devonian) rocks ranges from 1 to 10 percent, but content of the Silurian rocks can reach 16 percent (Makhous and others, 1997). Middle to Upper Devonian and Carboniferous rocks contain from 0.5 to 2.5 percent TOC (Makhous and others, 1997). In the Takhoukht area west of and adjacent to Hassi Messaoud field (fig. 3), equivalent vitrinite reflectance value of Silurian source rocks is 0.7 percent R_o (calculated, Makhous and others, 1997). Silurian source rocks are more mature in western and southern portions of the Oued Mya Basin (Daniels and Emme, 1995; Makhous and others, 1997). In the southern portion of the basin, equivalent vitrinite reflectance values of Silurian source rocks range from 1.3 to 1.7 percent R_o (calculated, Makhous and others, 1997). Equivalent vitrinite reflectance values of the Middle to Upper Devonian and the Carboniferous range from 0.7 to 1.5 percent R_o (calculated, Makhous and others, 1997).

Minor amounts of petroleum may have been generated in the southern portion of the Oued Mya Basin during the Carboniferous when the Paleozoic section was thickest, but generation was halted during Hercynian deformation (Makhous and others, 1997; Boote and others, 1998). The main phase of oil generation occurred after Hercynian deformation with the development of the new Triassic Basin depocenter, superimposed on the northern part of the Oued Mya Basin. Oil generation and migration most likely started no earlier than Late Triassic and peaked in Late Cretaceous to early Tertiary (Makhous and others, 1997; Boote and others, 1998). Oil generated in the Oued Mya Total Petroleum System also charged the Hassi R'Mel area on the Tilrhemt Arch. (The Hassi R'Mel area was either simultaneously or subsequently charged with gas from the north and west and is therefore included in another total petroleum system.) Pyrenean uplift and erosion terminated petroleum generation in the Oued Mya Basin (Boote and others, 1998). Petroleum most likely migrated laterally into adjacent or juxtaposed migration conduits and reservoirs. Some vertical migration may have occurred along faults or fractures in structurally deformed areas (Boote and others, 1998).

Overburden Rocks

Overburden rocks are variable across the area mainly due to nondeposition and erosion during the Hercynian, Austrian, and Pyrenean deformational events (fig. 4*B*). Large portions of Paleozoic section were removed by erosion during Hercynian deformation, as much as 2,200 m of Silurian and Devonian sediments (Makhous and others, 1997). Mesozoic rocks comprise most of the overburden and unconformably overlie the Paleozoic section throughout the total petroleum system. Only small sections of Mesozoic rocks were removed by erosion. Both Paleozoic and Mesozoic rocks are thickest in the central part of the basin between the Tilrhemt Arch and the Amguid-Hassi Touareg structural axis (fig. 4*B*) (Boudjema, 1987; van de Weerd and Ware, 1994). A thin Cenozoic section is present over part of the total petroleum system.

Reservoir Rocks

Known reservoir rocks in the Tanezzuft-Oued Mya Total Petroleum System are predominately Cambrian-Ordovician and Triassic sandstone (Petroconsultants, 1996a). Cambrian-Ordovician reservoirs include fluvial to marine sandstone of the Cambrian Hassi Messaoud and Ordovician Gres d'El Atchane (van de Weerd and Ware, 1994; Petroconsultants, 1996a). The Triassic reservoirs include fluvial sandstone of the Trias Argilo-Greseux Inferieur and Trias Argilo-Greseux Carbonate (Petroconsultants, 1996a). Other reservoirs include fluvial, deltaic, and marine sandstone within the Ordovician to Silurian M'Kratta Complex. Names of laterally equivalent rock units are shown in figure 5, and known reservoir properties are given in table 2.

Seal Rocks

As much as 2,000 m of Triassic to Jurassic evaporites, mudstone, and carbonate rocks (Saliferous Units, fig. 5) provides a regional top seal for reservoirs in most of the Tanezzuft-Oued Mya Total Petroleum System. The Triassic to Jurassic seal extends from the Saharan Flexure in the north where the thickest section is present to approximately the southern boundary of the Trias/Ghadames Province (fig. 1). Triassic volcanic rocks provide the primary seal for some reservoirs, and intraformational Paleozoic marine mudstone provides secondary, lateral seals when in conjunction with the regional top seal (Boote and others, 1998).

Trap Types in Oil and Gas Fields

Most of the accumulations discovered prior to 1996 are within anticlines and faulted anticlines (Boote and others, 1998; Petroconsultants, 1996a, van de Weerd and Ware, 1994). Some

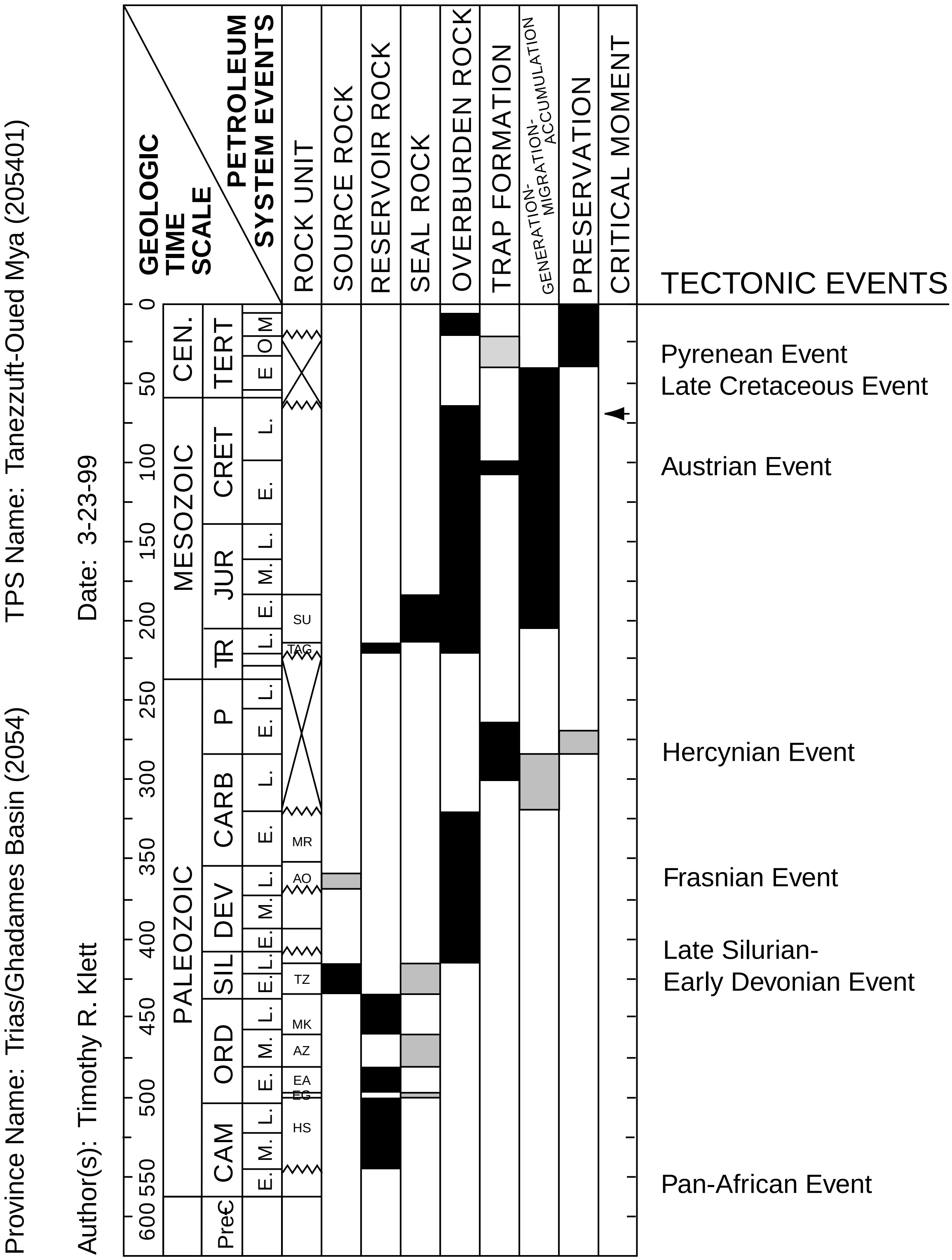


Figure 6. Events chart for Tanezzuft-Oued Mya Total Petroleum System. Names for abbreviations used in rock unit column are given in table 1. Gray boxes indicate secondary or possible occurrences.

accumulations within combination traps are present (Petroconsultants, 1996a).

The typical trapping style is structures directly overlain by or capped with Triassic to Jurassic evaporite sequence. Other proven and potential traps include (1) stratigraphic traps against volcanic rocks (Hamouda, 1980); (2) lateral sealing of reservoir rocks by impermeable formations due to lithofacies change, particularly Paleozoic reservoirs, or juxtaposed in fault blocks; and (3) incised valley fills associated with the Hercynian Unconformity.

All of the discovered petroleum accumulations in the Tanezzuft-Oued Mya Total Petroleum System are oil and are located in three groups along the flanks of the T-shaped anticlinorium (fig. 3). In the northwestern portion of the total petroleum system, along the Tilrhemt Arch, a cluster of several small oil accumulations is present in low-relief structures. These accumulations are more gas rich than others within the total petroleum system (Boote and others, 1998). In the northeast portion of the total petroleum system, where the Tilrhemt Arch intersects the Amguid-Hassi Touareg structural axis in the area surrounding the town of Ouargla, a cluster of larger, linearly oriented accumulations is present. The linear arrangement of these accumulations reflects the orientation of structural highs (Boote and others, 1998). The third group of accumulations is aligned on top of the Amguid-Hassi Touareg structural axis and includes the giant Hassi Messaoud oil field. Presumably, spillage from Hassi Messaoud charged other fields southwest along the structure (Boote and others, 1998).

Assessment of Undiscovered Petroleum by Assessment Unit

One assessment unit was identified for the Tanezzuft-Oued Mya Total Petroleum System, called Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit (fig. 3). As of 1996, it contained 36 fields. Of these discovered fields, 34 are oil fields, and 2 fields are not classified because they contain less than 1 million barrels of oil equivalent (MMBOE) (based on USGS oil and gas field definitions). Combined, these fields contain 10,843 MMBO and 8,973 BCFG, as known volumes (table 3) (Petroconsultants, 1996a). No gas fields have yet been discovered, and no natural gas liquids (NGL) volumes were reported. Minimum field sizes of 10 MMBO and 60 BCFG were chosen for this assessment unit based on the field-size distribution of discovered fields.

The exploration density as of 1996 was approximately seven new-field wildcat wells per 10,000 km^2. The overall success rate as of 1996 was approximately 24 discoveries per 100 new-field wildcat wells (or about one discovery per four new-field wildcat wells). Plots showing exploration activity and discovery history are presented in Appendix 1.

Exploration activity was not consistent through time: peaks in activity occurred during the early 1960's and mid- to late 1970's. The first major discovery was the giant Hassi Messaoud field in 1956. The sizes of oil fields discovered have generally decreased through time and with respect to exploration activity. Nevertheless, exploration appears to be relatively immature across much of the area. Fields equivalent in size to those found recently may yet be discovered. Discoveries of large fields, similar in size to those found early in the discovery history, are not likely. Oil will most likely be found along the anticlinorium, whereas gas would only be present in the southern and western portions of the total petroleum system. Adequate traps may not exist beyond the flanks of the anticlinorium.

Until recently, only structural traps had been explored for oil and gas. Before 1996, no discoveries have been made beyond the regional seal in the southern and western portions of the total petroleum system.

Continued exploration of structural and combination traps is expected for the next 30 years, and many more smaller oil fields could potentially be discovered along the flanks of the anticlinorium. New exploration concepts could include the search for both structural and stratigraphic traps in the southern portion of the total petroleum system, where perhaps some pre-Hercynian-generated petroleum, probably as gas, may be preserved.

This study estimates that about one-third of the total number of fields (discovered and undiscovered) of at least the minimum size has been discovered. Only a small number of undiscovered gas fields containing small volumes of gas was estimated. The estimated median size and number of undiscovered oil fields are 16 MMBO and 34 fields; the same values for undiscovered gas fields are 100 BCFG and 10 fields. The ranges of number, size, and coproduct-ratio estimates for undiscovered fields are given in table 4.

The estimated means of the undiscovered conventional petroleum volumes are 830 MMBO, 2,341 BCFG, and 110 MMBNGL (table 5). In addition, the mean size of the largest anticipated undiscovered oil field is 114 MMBO and gas field, 405 BCFG.

The Tanezzuft-Melrhir Total Petroleum System (205402)

As of 1996, the Tanezzuft-Melrhir Total Petroleum System was not a major oil and gas producing entity, although it was immature in terms of exploration. An events chart (fig. 7) summarizes the timing of sources, reservoirs, seals, trap development, and generation and migration of petroleum. Table 1 shows the formation names, ages, and lithology for abbreviations used in the events chart.

Source Rocks

The principal source rock in the Tanezzuft-Melrhir Total Petroleum System is the Silurian Tanezzuft Formation (or lateral equivalents). The extent and continuity of this source rock in the Melrhir Basin are not well defined (D. Boote, oral commun., 1999). The present-day TOC content of the Silurian source rocks in the Melrhir Basin ranges from 1.0 to 5.0 percent (Cunningham, 1988; Hammill and Robinson, 1992). Oil may have generated as early as Carboniferous or Permian time due to a thick wedge of Carboniferous to Permian sediments that was deposited in the northeastern portion of the Melrhir Basin (D. Boote, oral commun., 1999). The main phase of oil generation

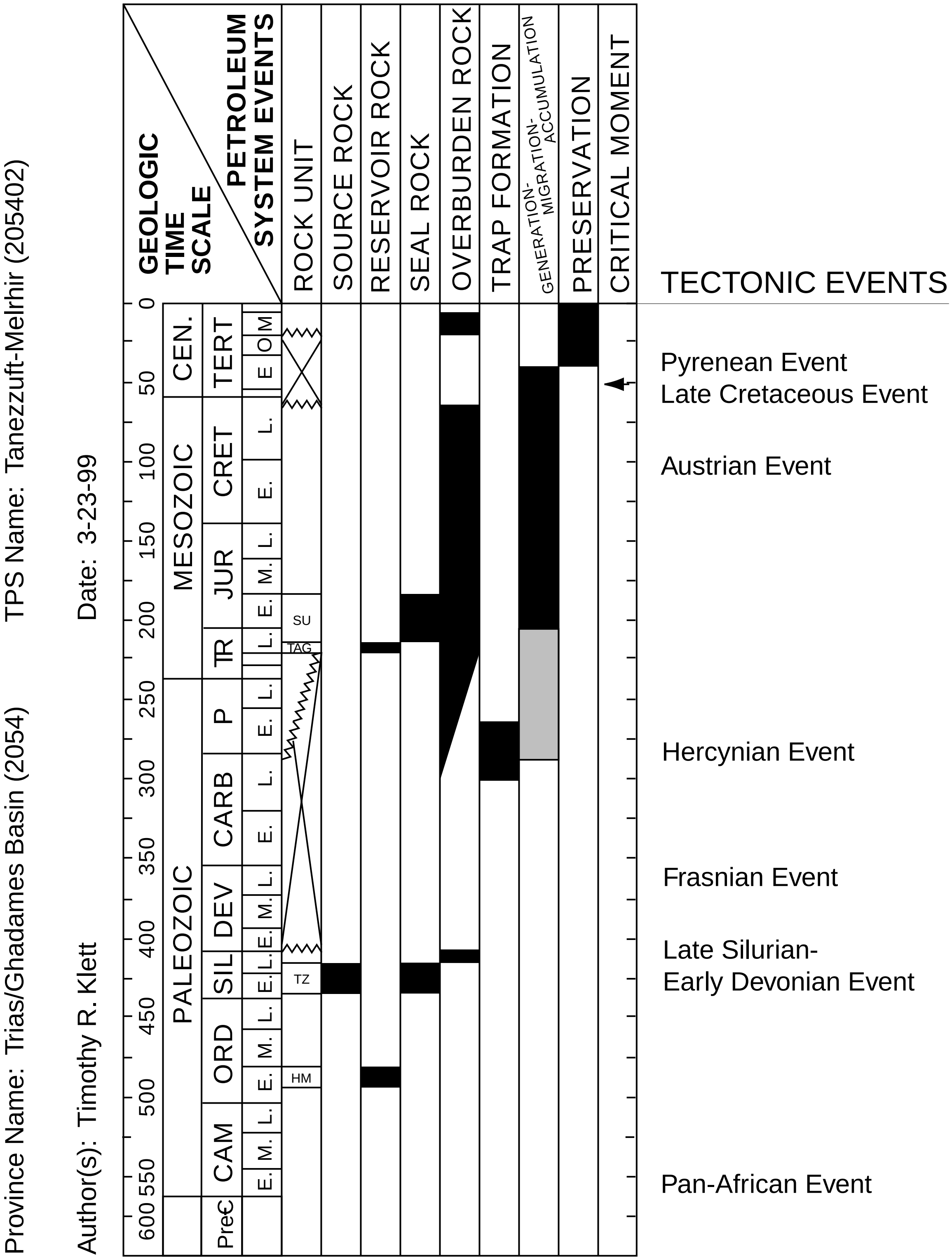


Figure 7. Events chart for Tanezzuft-Melrhir Total Petroleum System. Names for abbreviations used in rock unit column are given in table 1. Gray boxes indicate secondary or possible occurrences.

probably began in the Cretaceous and continued into the Tertiary (Rigo, 1996). The geochemistry of oils and source rocks of the Melrhir Basin is not well documented in literature available to the public. Petroleum most likely migrated laterally into adjacent or juxtaposed migration conduits and reservoirs. Some vertical migration may have occurred along faults or fractures (Boote and others, 1998).

Overburden Rocks

Overburden rocks are variable across the area mainly due to nondeposition and erosion during the Hercynian, Austrian, and Pyrenean deformational events. The largest portions of Paleozoic section were removed by erosion during Hercynian deformation. Paleozoic rocks are thickest to the north and thin to the south over the T-shaped anticlinorium. Mesozoic rocks comprise most of the overburden and unconformably overlie the Paleozoic section throughout the province. Only small sections of Mesozoic rocks were removed by erosion. A thin Cenozoic section is present over some parts of the area. Approximately 4,000 to more than 6,000 m of Mesozoic and Cenozoic overburden is present over the Tanezzuft-Melrhir Total Petroleum System (Cunningham, 1988; Hammil and Robinson, 1992; Rigo, 1996).

Reservoir Rocks

Known reservoir rocks in the Tanezzuft-Melrhir Total Petroleum System are predominately fluvial to marine sandstone of the Ordovician Hamra Formation and fluvial sandstone of the Triassic Kirchaou Formation, the lateral equivalent of the Trias Argilo-Greseux (Petroconsultants, 1996a). Names of other laterally equivalent rock units are given in figure 5. Known reservoir properties for the Tanezzuft-Melrhir Total Petroleum System are not shown in table 2 due to insufficient data.

Seal Rocks

Triassic to Jurassic evaporites, mudstone, and carbonate rocks (Saliferous Units, fig. 5) provide a regional top seal, and the Tanezzuft mudstone provides a secondary lateral seal when in conjunction with the top seal (Hammill and Robinson, 1992).

Trap Types in Oil and Gas Fields

Accumulations in three of the four fields discovered prior to 1996 are within tilted fault blocks, and in the fourth, within an arched stratigraphic trap (Hammill and Robinson, 1992; Rigo, 1996). The typical trapping style is structures directly overlain by or capped with Triassic to Jurassic evaporite sequence. Additional tilted fault blocks or other structures containing accumulations may exist along the Tilrhemt and Talemzane-Gefara Arches.

Assessment of Undiscovered Petroleum by Assessment Unit

One assessment unit was identified for the Tanezzuft-Melrhir Total Petroleum System, called Tanezzuft-Melrhir Structural/Stratigraphic Assessment Unit (fig. 3). As of 1996, it contained a total of four fields, two oil fields and two gas fields (based on USGS oil and gas field definitions). Combined, these fields contain 6 MMBO, 125 BCFG, and 9 MMBNGL, as known volumes (table 3) (Petroconsultants, 1996a). Minimum field sizes of 1 MMBO and 6 BCFG were chosen for this assessment unit due to the relatively small sizes of discovered fields.

The exploration density as of 1996 was approximately four new-field wildcat wells per 10,000 km^2. The overall success rate as of 1996 was four discoveries with 47 new-field wildcat wells (or about one discovery per 12 new-field wildcat wells).

Exploration activity was sparse and not consistent through time. Exploration is immature across the area. As more areas are explored, field sizes equivalent to those found recently may be discovered. Discoveries of large fields, similar in size to those found early in the discovery history, are likely, but adequate traps may not exist beyond the flanks of the anticlinorium.

Until recently, only structural traps had been explored for oil and gas. Continued exploration of structural and perhaps combination traps is expected for the next 30 years, and more discoveries could be made along the flanks of the Tilrhemt and Talemzane-Gefara Arches. Permian-aged reefs containing Silurian-sourced petroleum accumulations may exist in the eastern part of this total petroleum system, in Tunisia (Rigo, 1995), but many of these reefs have been tested with little or no success (D. Boote, oral commun., 1999).

This study estimates that only a very small fraction of the total number of fields (discovered and undiscovered) of at least the minimum size has been discovered. The estimated median size and number of undiscovered oil fields are 16 MMBO and 31 fields; the same values for undiscovered gas fields are 70 BCFG and 15 fields. The ranges of number, size, and coproduct-ratio estimates for undiscovered fields are given in table 4.

The estimated means of the undiscovered conventional petroleum volumes are 1,875 MMBO, 4,887 BCFG, and 269 MMBNGL (table 5). In addition, the mean of the largest anticipated undiscovered oil field is 550 MMBO and undiscovered gas field, 686 BCFG.

The Tanezzuft-Ghadames Total Petroleum System (205403)

The Tanezzuft-Ghadames Total Petroleum System is an important total petroleum system with respect to known oil and gas volumes, containing about 30 percent of the discovered oil and 60 percent of the discovered gas in the province. A small portion of this total petroleum system extends into the neighboring Illizi, Hamra, and Pelagian Provinces. Although Middle to

Upper Devonian-aged mudstone may be the primary source rock, the naming convention requires that the oldest source rock, Tanezzuft, must be used in the total petroleum system name. An events chart (fig. 8) summarizes the timing of sources, reservoirs, seals, trap development, and generation and migration of petroleum. Table 1 shows the formation names, ages, and lithology for abbreviations used in the events chart.

Source Rocks

Two major source rocks generated petroleum in the Tanezzuft-Ghadames Total Petroleum System, the Silurian Tanezzuft Formation (or lateral equivalents) and Middle to Upper Devonian mudstone (Tissot and others, 1973; Daniels and Emme, 1995). Based on regional stratigraphic architecture of the Ghadames (Berkine) Basin and geochemical analysis, Daniels and Emme (1995) indicated that the Upper Devonian (Frasnian) mudstone may be the primary source rock.

In the Ghadames (Berkine) Basin, mean present-day TOC content of Silurian source rocks ranges from 0.5 to 2.0 percent (individual values as high as 17 percent), and that of Middle to Upper Devonian source rocks ranges from 2.0 to 8.0 percent (individual values as high as 14 percent) (Daniels and Emme, 1995; Makhous and others, 1997). Equivalent vitrinite reflectance of Silurian source rocks ranges from 1.1 to 2.0 percent R_o and Upper Devonian, from 1.1 to 1.3 percent R_o (Daniels and Emme, 1995). Source rock maturity is variable across the total petroleum system. In the northern part of the total petroleum system, Silurian source rocks are presently in the peak to late oil generation phase, whereas Middle to Upper Devonian source rocks are presently in the early to peak oil generation window (Daniels and Emme, 1995). In the central part, Silurian rocks are presently in the wet to dry gas generation phase, whereas Middle to Upper Devonian source rocks are presently in the late oil to early wet gas generation phase (Daniels and Emme, 1995).

Petroleum generation in the Ghadames (Berkine) Basin may have taken place in two pulses, the first occurring in the Carboniferous before Hercynian deformation and the second occurring after Hercynian deformation and the development of the Triassic Basin (Daniels and Emme, 1995; Makhous and others, 1997). Peak oil generation from Silurian source rocks began in the middle Cretaceous in the northern portion of the total petroleum system (Daniels and Emme, 1995). In the central portion, peak oil generation from Silurian source rocks began as early as the Carboniferous, was interrupted by the Hercynian event, then resumed until Late Jurassic (Daniels and Emme, 1995). Oil generation from Middle to Upper Devonian source rocks peaked in early Tertiary in the northern portion of the total petroleum system and peaked in Early Cretaceous in the central portion (Daniels and Emme, 1995). Petroleum most likely migrated laterally into adjacent or juxtaposed migration conduits and reservoirs. Some vertical migration may have occurred along faults or fractures in structurally deformed areas (Boote and others, 1998).

Overburden Rocks

Overburden rocks are variable across the area mainly due to nondeposition and erosion during the Hercynian, Austrian, and Pyrenean deformational events (fig. 4*A* and *B*). Large portions of Paleozoic section were removed by erosion during Hercynian deformation, between 380 and 3,000 m of sediments, or more, were eroded during Hercynian deformation (Malla and others, 1997). Paleozoic rocks are thickest to the southeast (approximately 2,300 m) and thin to the west and north over the T-shaped anticlinorium. Mesozoic rocks comprise most of the overburden and overlie the Paleozoic section above the Hercynian Unconformity throughout the province. Only small sections of Mesozoic rocks were removed by erosion. Mesozoic rocks are thickest to the north and west and thin to the southeast (fig. 4*A* and *B*) (Bishop, 1975; Chiarelli, 1978; Boudjema, 1987; Montgomery, 1993). A thin Cenozoic section is present over part of the area.

Reservoir Rocks

The known major reservoir rocks in the Tanezzuft-Ghadames Total Petroleum System are fluvial to marine sandstone of the Cambrian-Ordovician and fluvial sandstone of the Triassic (Trias Argilo-Greseux). Cambrian-Ordovician reservoirs include the Cambrian Hassi Messaoud Formation, Hassi Leila Formation, and Quartzites de Hamra (laterally equivalent to the Haouaz Formation) (Petroconsultants, 1996a; van de Weerd and Ware, 1994). The Triassic lower clastic unit reservoirs include sandstone of the Trias Argilo-Greseux Inferieur (Nezla Formation, Ouled Chebbi Formation, and Ras Hamia Formation) as well as sandstone of the Trias Argilo-Greseux Superieur (Gassi Touil Formation and Zarzaitine Sandstone), the Kirchaou Sandstone, and the Tartrat Sandstone (Petroconsultants, 1996a).

The marginal marine to marine sandstone of the Upper Silurian Acacus Formation is a predominant reservoir in the eastern portion of the Tanezzuft-Ghadames Total Petroleum System (Petroconsultants, 1996a). Other reservoir rocks in the Tanezzuft-Ghadames Total Petroleum System include glacial and marine sandstone of the Ordovician to Silurian M'Kratta Complex; the paralic to marine Lower Devonian F6 sandstone (Tadrart Formation) and Upper Devonian Ouan Kasa Formation; and the deltaic and marine Lower Carboniferous Tahara Formation (Petroconsultants, 1996a). Names of some laterally equivalent rock units are shown in figure 5, and known reservoir properties are given in table 2.

Seal Rocks

Triassic to Jurassic evaporites, mudstone, and carbonate rocks (Saliferous Units, fig. 5) provide a regional top seal. Intraformational Paleozoic marine mudstone is the primary seal for some reservoirs (Boote and others, 1998).

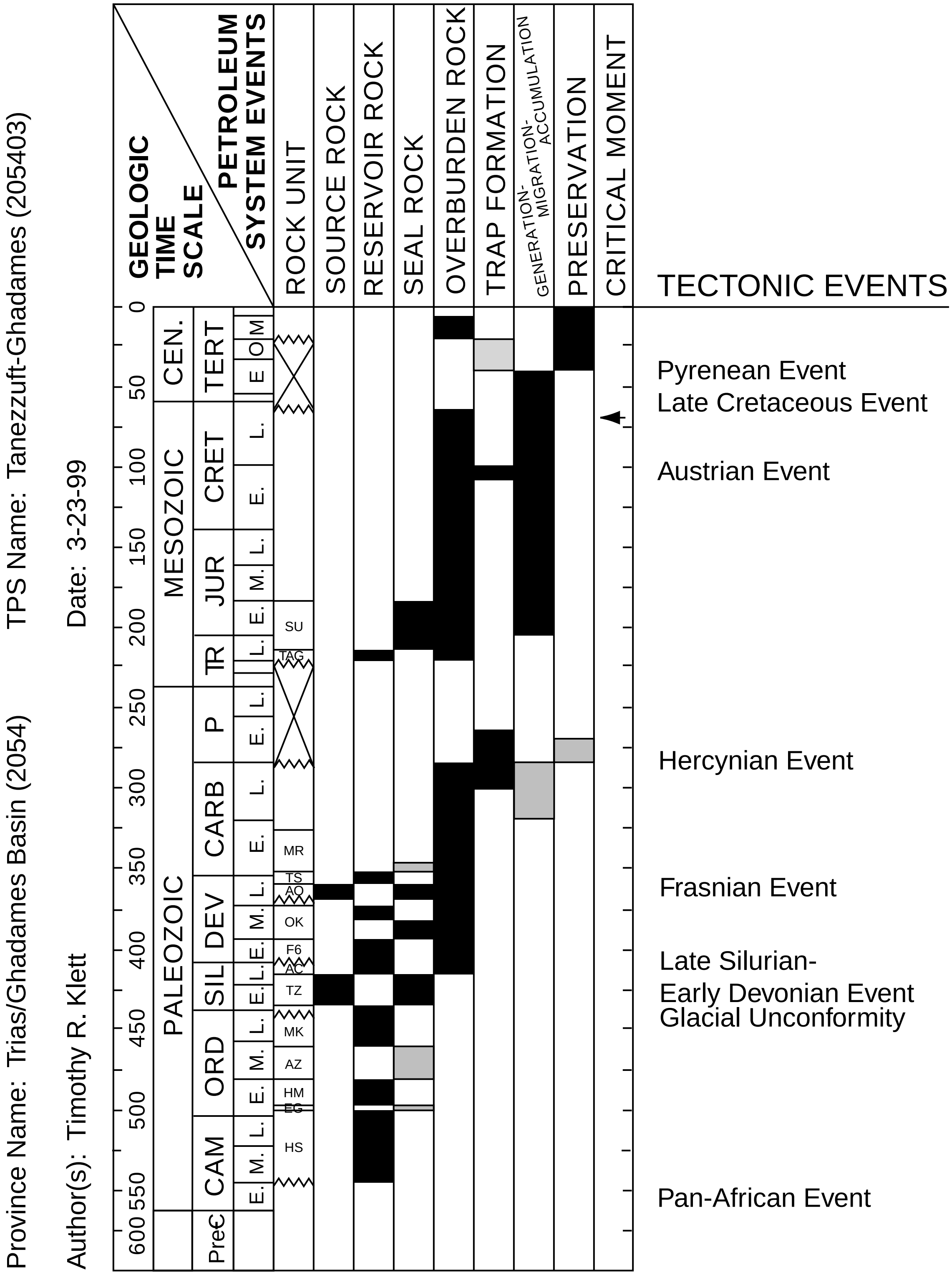


Figure 8. Events chart for Tanezzuft-Ghadames Total Petroleum System. Names for abbreviations used in rock unit column are given in table 1. Gray boxes indicate secondary or possible occurrences.

Trap Types in Oil and Gas Fields

Most of the accumulations discovered prior to 1996 are within anticlines, faulted anticlines, or fault blocks (Echikh, 1998; Boote and others, 1998; Petroconsultants, 1996a, van de Weerd and Ware, 1994). A few accumulations within combination traps are present (Echikh, 1998).

The typical trapping style is structures directly overlain by or capped with Triassic to Jurassic evaporite sequence. Other proven or potential traps include combination traps in association with intraformational mudstone or volcanic rocks, if present, and incised valley fills associated with the Hercynian Unconformity.

The discovered petroleum accumulations in the Tanezzuft-Ghadames Total Petroleum System exist in low-relief structures in the central and northeast portions of the total petroleum system and in high-relief structures along the Amguid-Hassi Touareg structural axis (fig. 1). Three accumulations along the Amguid-Hassi Touareg structural axis are more gas rich than others within the total petroleum system (fig. 1). Several small fields are producing from Silurian Acacus reservoirs in low-relief structures in the extreme eastern part of the total petroleum system (in Libya and Tunisia) (fig. 2). In the northern part of the total petroleum system, along the Talemzane-Gefara Arch, some undiscovered accumulations might be present in tilted fault blocks that mirror those across the arch in the Tanezzuft-Melrhir Total Petroleum System.

Assessment of Undiscovered Petroleum by Assessment Unit

One assessment unit was identified for the Tanezzuft-Ghadames Total Petroleum System, called Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit (fig. 3). As of 1996, it contained 93 fields. Of these discovered fields, 66 are oil fields, 21 are gas fields, and 6 fields are not classified because they contain less than 1 MMBOE. Combined, these fields contain 4,538 MMBO, 16,484 BCFG, and 1,011 MMBNGL, as known volumes (table 3) (Petroconsultants, 1996a). Minimum field sizes of 1 MMBO and 6 BCFG were chosen for this assessment unit based on the field-size distribution of discovered fields.

The exploration density as of 1996 was approximately 15 new-field wildcat wells per 10,000 km^2. The overall success rate as of 1996 was approximately 32 discoveries per 100 new-field wildcat wells (or about one discovery per three new-field wildcat wells). The greatest success in terms of discoveries per number of new-field wildcat wells drilled occurred since the mid-1980's through 1995. Plots showing exploration activity and discovery history are presented in Appendix 2.

Exploration activity was not consistent through time: peaks occurred in activity from the early 1960's to the early 1970's, and again in the 1980's. The sizes of oil and gas fields discovered have generally decreased through time and with respect to exploration activity, but some large accumulations are still being discovered. Exploration appears to be moderately mature across much of the area.

Until recently, only structural traps had been explored for oil and gas. Continued exploration of structural and combination traps is expected for the next 30 years, and many more fields, both oil and gas, could be discovered, especially in deeper sections within the center of the Ghadames (Berkine) Basin (Macgregor, 1998). New exploration concepts could include the search for both structural and stratigraphic traps. Additionally, pinchouts within the Silurian Acacus sandstone have some potential, but seals are lacking in much of the total petroleum system due to erosional truncation (Echikh, 1998). Potential for discoveries exists in stratigraphic traps, due to the abundance of clastic reservoirs and unconformities (Macgregor, 1998) and in possible tilted fault block traps along the Talemzane-Gefara Arch (similar to those in the Tanezzuft-Melrhir Total Petroleum System).

This study estimates that about one-half of the total number of fields (discovered and undiscovered) of at least the minimum size has been discovered. The estimated median size and number of undiscovered oil fields are 16 MMBO and 73 fields; the same values for undiscovered gas fields are 70 BCFG and 38 fields. The ranges of number, size, and coproduct-ratio estimates for undiscovered fields are given in table 4.

The estimated means of the undiscovered conventional petroleum volumes are 4,461 MMBO, 12,035 BCFG, and 908 MMBNGL (table 5). In addition, the mean size of the largest anticipated undiscovered oil and gas fields are 817 MMBO and 1,014 BCFG, respectively.

Summary

Three “composite” total petroleum systems were identified, each coinciding with a separate basin and each comprising a single assessment unit. These total petroleum systems are called the Tanezzuft-Oued Mya, Tanezzuft-Melrhir, and Tanezzuft-Ghadames.

The main source rocks are the Silurian Tanezzuft Formation (or lateral equivalents) and Middle to Upper Devonian mudstone. Petroleum generation and migration may have started as early as the Carboniferous Period but was halted during the Hercynian deformational event. Peak generation and migration occurred from the Cretaceous to the Tertiary. The major reservoir rocks are Cambrian to Ordovician, Silurian, Devonian, Carboniferous, and Upper Triassic sandstone. Triassic to Jurassic evaporites, mudstone, carbonate rocks, and volcanic rocks provide a regional top seal for most of the accumulations, while Paleozoic marine mudstone locally provides seals. In the fields discovered thus far, traps are primarily structural and associated with anticlines and faulted anticlines.

The estimated means of the undiscovered conventional petroleum volumes in the Tanezzuft-Oued Mya Total Petroleum System are 830 MMBO, 2,341 BCFG, and 110 MMBNGL; volumes in the Tanezzuft-Melrhir Total Petroleum System are 1,875 MMBO, 4,887 BCFG, and 269 MMBNGL; and volumes in the Tanezzuft-Ghadames Total Petroleum System are 4,461 MMBO, 12,035 BCFG, and 908 MMBNGL. The combined estimated means of the undiscovered conventional volumes for these total

petroleum systems in the Trias/Ghadames Province are 7,167 MMBO, 19,262 BCFG, and 1,288 MMBNGL.

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Table 1. Abbreviations, names, ages, and lithology of formations used in the total petroleum system events chart.

Code	Formation name	Age	Lithology
AC	Acacus	Upper Silurian	Sandstone
AO	Aouinet Ouenine	Middle to Upper Devonian	Mudstone
AZ	Argiles D'Azzel	Middle Ordovician	Mudstone
SU	Saliferous Units	Lower Jurassic	Salt and anhydrite
EA	Gres D'El Atchane	Lower Ordovician	Sandstone
EG	Argile D'El Gassi	Lower Ordovician	Mudstone
F6	F6 Sandstone Member	Lower Devonian	Sandstone
HM	Hamra	Lower Ordovician	Sandstone
HS	Hassaouna	Cambrian-Ordovician	Sandstone
MK	M'Kratta Complex	Middle to Upper Ordovician	Sandstone and mudstone
MR	Mrar	Lower Carboniferous	Mudstone and sandstone
OK	Ouan Kasa	Middle Devonian	Mudstone and sandstone
TAG	Trias Argilo-Greseux	Upper Triassic	Sandstone
TS	Tahara (Shatti)	Upper Devonian to Lower Carboniferous	Sandstone
TZ	Tanezzuft	Silurian	Mudstone

Table 2. Reservoir properties of discovered accumulations for each assessment unit through 1995. [nd, represents either no data or insufficient data. Data from Petroconsultants (1996a)]

USGS Code	Depth (meters)				Gross thickness (meters)				Porosity (percent)				Permeability (millidarcies)			
	Minimum	Mean	Maximum	Number	Minimum	Mean	Maximum	Number	Minimum	Mean	Maximum	Number	Minimum	Mean	Maximum	Number
205401	**Tanezzuft-Oued Mya Total Petroleum System**															
20540101	Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit															
Triassic	2,500	3,372	3,871	28	10	58	200	18	12	19	20	26	100	505	1,000	26
Silurian	3,503	3,823	4,169	4	8	12	15	4	7	7	7	4	0.2	0.2	0.2	4.0
Cambrian-Ordovician	2,900	3,312	4,000	11	18	80	145	8	10	17	25	9	9	408	1,000	8
205402	**Tanezzuft-Melrhir Total Petroleum System**															
20540201	Tanezzuft-Melrhir Structural/Stratigraphic Assessment Unit															
Triassic	nd	nd	nd	1	nd	nd	nd	1	nd	nd	nd	1	nd	nd	nd	1
Cambrian-Ordovician	nd	nd	nd	3	nd	nd	nd	3	nd	nd	nd	2	nd	nd	nd	1
205403	**Tanezzuft-Ghadames Total Petroleum System**															
20540301	Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit															
Triassic	100	2,461	4,188	49	12	85	365	28	9	20	35	47	25	756	1,400	42
Carboniferous	1,829	2,810	3,400	3	30	30	30	1	20	22	25	3	100	200	250	3
Devonian	2,217	3,435	4,000	16	12	95	200	4	15	20	23	4	20	1,039	2,000	4
Silurian	1,219	2,729	3,127	33	15	51	163	33	14	19	30	31	50	118	300	30
Cambrian-Ordovician	152	2,860	4,000	10	14	201	759	7	6	9	12	9	0.2	254	1,000	8

Table 3. Number and sizes of discovered fields for each assessment unit through 1995. The Tanezzuft-Oued Mya Total Petroleum System contains the greatest volume of discovered oil, whereas the Tanezzuft-Ghadames Total Petroleum System contains the greatest volume discovered gas and natural gas liquids. [MMBO, million barrels of oil; BCFG, billion cubic feet of gas; NGL, natural gas liquids; MMBNGL, million barrels of NGL. Volumes reported are summed for oil and gas fields (USGS defined). Oil and gas fields containing known volumes below 1 million barrels of oil or 6 billion cubic feet of gas (BCFG) are grouped. Data from Petroconsultants (1996a)]

USGS Code	Number of fields	Known (discovered) volumes		
		Oil (MMBO)	Gas (BCFG)	NGL (MMBNGL)
205401	**Tanezzuft-Oued Mya Total Petroleum System**			
20540101	Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit			
Oil fields	34	10,842	8,970	0
Gas fields	0	0	0	0
Fields < 1 MMBOE	2	1	3	0
All fields	36	10,843	8,973	0
205402	**Tanezzuft-Melrhir Total Petroleum System**			
20540201	Tanezzuft-Melrhir Structural/Stratigraphic Assessment Unit			
Oil fields	2	6	0	0
Gas fields	2	0	125	9
Fields < 1 MMBOE	0	0	0	0
All fields	4	6	125	9
205403	**Tanezzuft-Ghadames Total Petroleum System**			
20540301	Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit			
Oil fields	66	4,385	5,327	63
Gas fields	21	151	11,154	948
Fields < 1 MMBOE	6	2	3	0
All fields	93	4,538	16,484	1,011
2054	***Total***			
Oil fields	102	15,233	14,297	63
Gas fields	23	151	11,279	957
Fields < 1 MMBOE	8	2	6	0
All fields	133	15,384	25,576	1,020

Table 4. Estimated sizes, number, and coproduct ratios of undiscovered oil and gas fields for each assessment unit. [MMBO, million barrels of oil; BCFG, billion cubic feet of gas; CFG/BO, cubic feet of gas per barrel oil, not calculated for gas fields; BNGL/MMCFG or BL/MMCFG, barrels of natural gas liquids or barrels of total liquids per million cubic feet of gas. BNGL/MMCFG was calculated for USGS-defined oil fields whereas BL/MMCFG was calculated for USGS-defined gas fields. Shifted mean, the mean size of the accumulation within a lognormal distribution of field sizes for which the origin is the selected minimum field size]

USGS Code	Size of accumulations (MMBO or BCFG)					Number of accumulations					Gas-to-oil ratio (CFG/BO)					NGL-to-gas ratio (BNGL/MMCFG)				
	Minimum	Median	Maximum	Mean	Shifted mean	Minimum	Median	Maximum	Mean	Mode	Minimum	Median	Maximum	Mean	Mode	Minimum	Median	Maximum	Mean	Mode
205401	**Tanezzuft-Oued Mya Total Petroleum System**																			
20540101	Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit																			
Oil fields	10	16	362	14	24	4	34	70	35	31	434	868	1,302	867	868	20	40	60	40	40
Gas fields	60	100	2,000	85	145	1	10	30	11	2						25	50	75	50	50
205402	**Tanezzuft-Melrhir Total Petroleum System**																			
20540201	Tanezzuft-Melrhir Structural/Stratigraphic Assessment Unit																			
Oil fields	1	16	2,488	55	56	3	31	81	34	17	686	1,372	2,058	1,372	1,372	20	40	60	40	40
Gas fields	6	70	3,144	136	142	2	15	38	16	9						36	72	108	72	72
205403	**Tanezzuft-Ghadames Total Petroleum System**																			
20540301	Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit																			
Oil fields	1	16	2,488	55	56	14	73	202	80	25	686	1,372	2,058	1,371	1,372	20	40	60	40	40
Gas fields	6	70	3,110	136	142	6	38	105	42	14						56	112	168	112	112

Table 5. Estimated undiscovered conventional oil, gas, and natural gas liquids volumes for oil and gas fields for each assessment unit. [MMBO, million barrels of oil; BCFG, billion cubic feet of gas; NGL, natural gas liquids; MMBNGL, million barrels of natural gas liquids. Volumes of undiscovered NGL were calculated for oil fields whereas volumes of total liquids (oil plus NGL) were calculated for USGS-defined gas fields. Largest anticipated undiscovered field is in units of MMBO for oil fields and BCFG for gas fields. Results shown are estimates that are fully risked with respect to geology and accessibility. Undiscovered volumes in fields smaller than the selected minimum field size are excluded from the assessment. Means can be summed, but fractiles (F95, F50, and F5) can be summed only if a correlation coefficient of +1.0 is assumed]

USGS Code	MFS	Prob. (0-1)	Undiscovered conventional volumes												Largest anticipated undiscovered field (MMBO or BCFG)			
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)							
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
205401	**Tanezzuft-Oued Mya Total Petroleum System**																	
20540101	Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit																	
Oil fields	10	1.00	292	802	1,450	830	233	673	1,355	720	9	26	58	29	40	96	255	114
Gas fields	60	1.00					269	1,417	3,640	1,621	13	69	192	81	111	318	1,030	405
All fields			292	802	1,450	830	502	2,090	4,994	2,341	21	95	250	110				
205402	**Tanezzuft-Melrhir Total Petroleum System**																	
20540201	Tanezzuft-Melrhir Structural/Stratigraphic Assessment Unit																	
Oil fields	1	1.00	348	1,629	4,224	1,875	450	2,175	6,079	2,574	17	84	252	103	96	403	1,557	550
Gas fields	6	1.00					495	2,032	5,060	2,313	33	142	382	166	160	539	1,756	686
All fields			348	1,629	4,224	1,875	945	4,206	11,139	4,887	50	226	635	269				
205403	**Tanezzuft-Ghadames Total Petroleum System**																	
20540301	Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit																	
Oil fields	1	1.00	990	3,993	9,520	4,461	1,274	5,292	13,733	6,110	48	206	576	244	197	679	1,939	817
Gas fields	6	1.00					1,403	5,311	12,469	5,925	148	576	1,480	664	299	865	2,285	1,014
All fields			990	3,993	9,520	4,461	2,677	10,603	26,201	12,035	196	782	2,055	908				

Table 5. Continued.

USGS Code	MFS	Prob. (0-1)	Undiscovered conventional volumes												Largest anticipated undiscovered field (MMBO or BCFG)			
			Oil (MMBO)				Gas (BCFG)				NGL (MMBNGL)							
			F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean	F95	F50	F5	Mean
2054	***Total***																	
	Oil fields		1,630	6,424	15,194	7,167	1,957	8,140	21,166	9,403	74	316	886	376				
	Gas fields						2,167	8,759	21,168	9,859	194	786	2,054	911				
	All fields		1,630	6,424	15,194	7,167	4,125	16,899	42,334	19,262	268	1,102	2,940	1,288				

APPENDICES

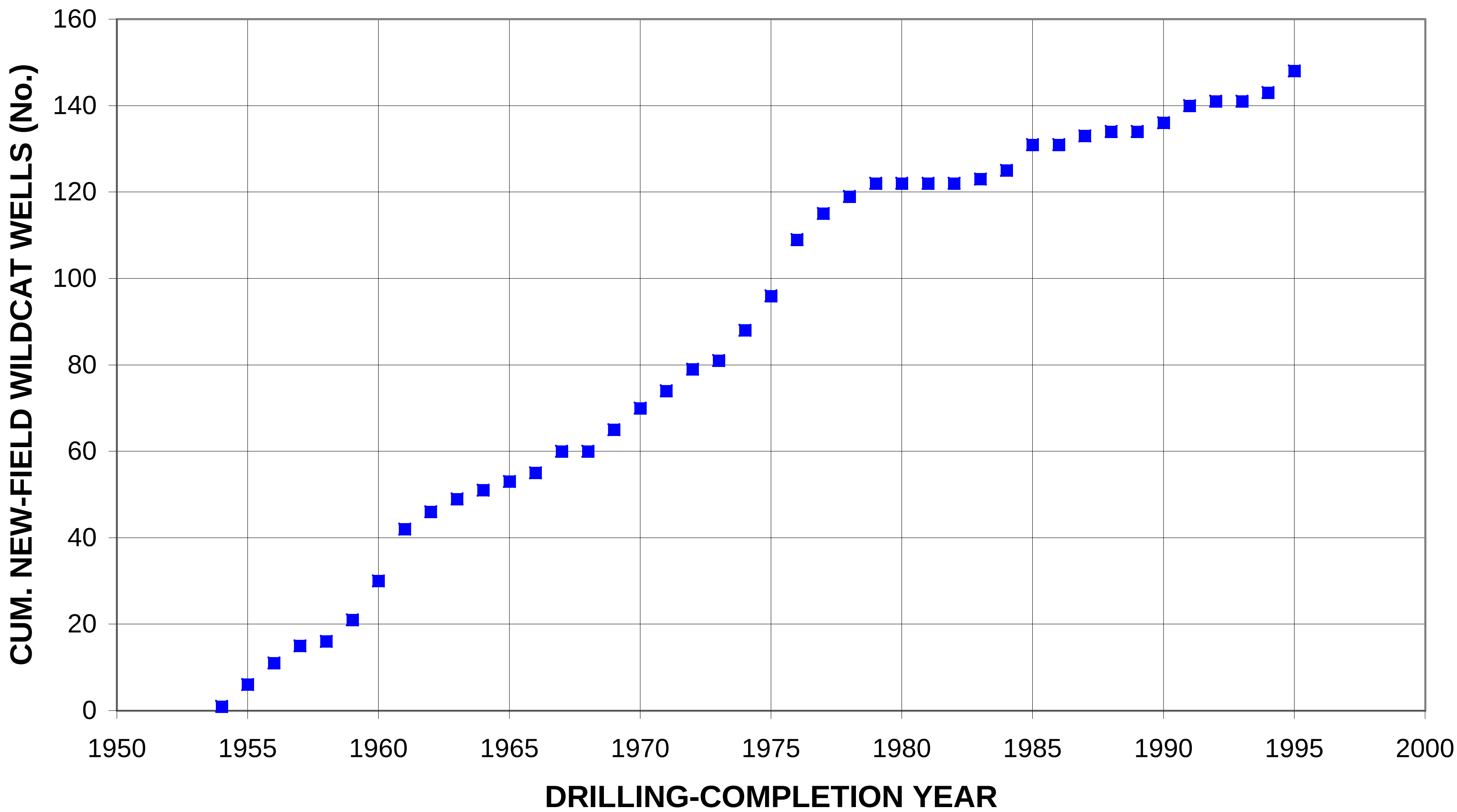
Exploration-activity and discovery-history plots for each of the assessment units. Two sets of plots and statistics are provided, one set showing known field sizes (cumulative production plus remaining reserves) and another showing field sizes upon which a reserve-growth function was applied (labeled grown). Within each set of plots, oil fields and gas fields are treated separately. The plots include:

- Cumulative Number of New-Field Wildcat Wells vs. Drilling-Completion Year
- Number of New-Field Wildcat Wells vs. Drilling-Completion Year
- Oil- or Gas-Field Size (MMBO or BCFG) vs. Oil- or Gas-Field Rank by Size (With Respect to Discovery Halves or Thirds)
- Number of Oil or Gas Fields vs. Oil- or Gas-Field Size Classes (MMBO or BCFG) (With Respect to Discovery Halves or Thirds)
- Volume of Oil or Gas (MMBO or BCFG) vs. Oil- or Gas-Field Size Classes (MMBO or BCFG)
- Oil- or Gas-Field Size (MMBO or BCFG) vs. Field-Discovery Year
- Oil- or Gas-Field Size (MMBO or BCFG) vs. Cumulative Number of New-Field Wildcat Wells
- Cumulative Oil or Gas Volume (MMBO or BCFG) vs. Field-Discovery Year
- Cumulative Oil or Gas Volume (MMBO or BCFG) vs. Cumulative Number of New-Field Wildcat Wells
- Cumulative Number of Oil or Gas Fields vs. Field-Discovery Year

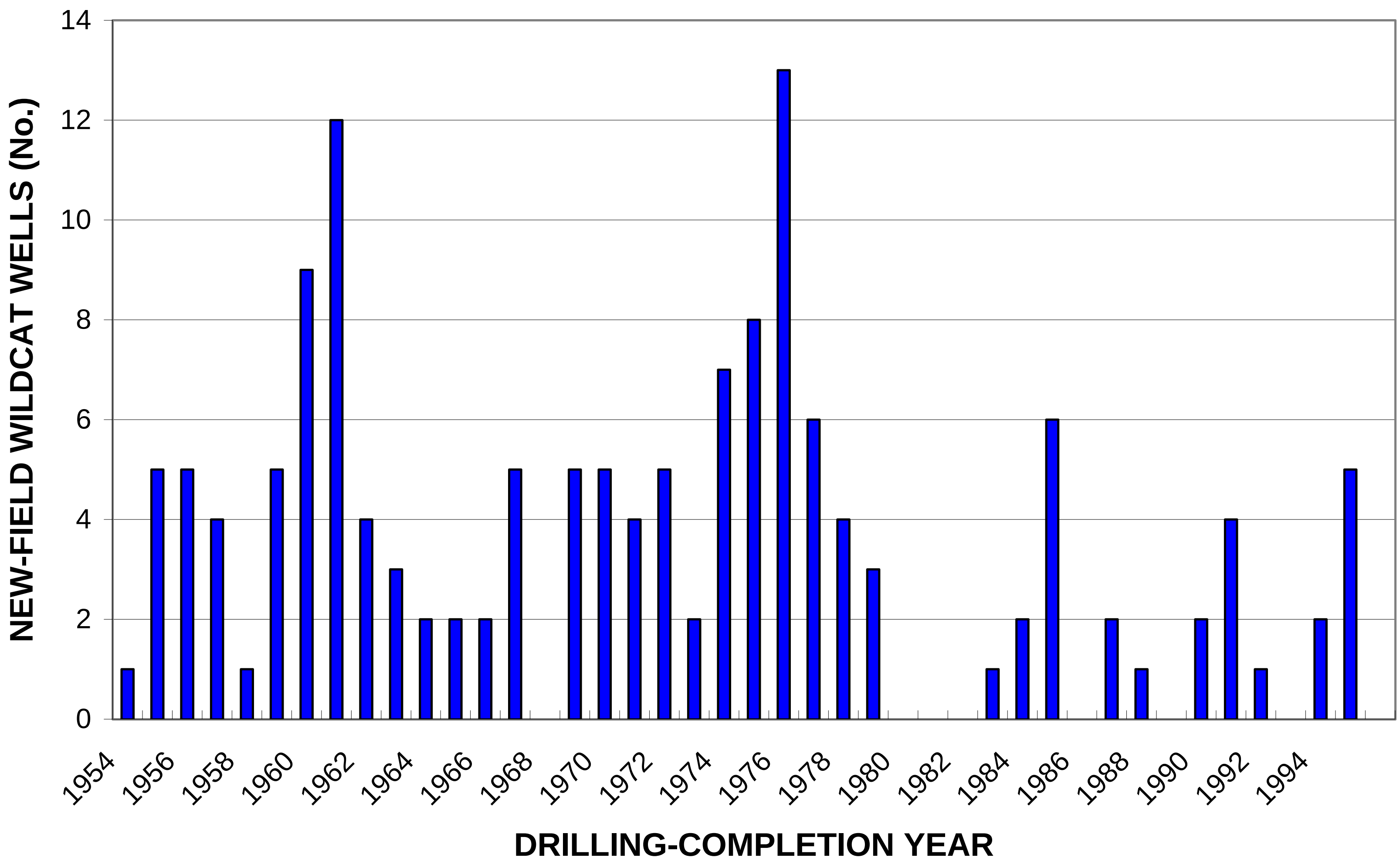
- Cumulative Number of Oil or Gas Fields vs. Cumulative Number of New-Field Wildcat Wells
- Reservoir Depth, Oil or Gas Fields (m) vs. Field-Discovery Year
- Reservoir Depth, Oil or Gas Fields (m) vs. Cumulative Number of New-Field Wildcat Wells
- Gas/Oil, Oil Fields (CFG/BO) vs. Mean Reservoir Depth (m)
- NGL/Gas, Oil Fields (BNGL/MMCFG) vs. Mean Reservoir Depth (m)
- Liquids/Gas, Gas Fields (BL/MMCFG) vs. Mean Reservoir Depth (m)
- Number of Reservoirs in Oil Fields vs. API Gravity (Degrees)

Appendix 1. Exploration-activity and discovery-history plots for the Tanezzuft-Oued Mya Structural/Stratigraphic Assessment Unit.

Tanezzuft-Oued Mya Structural/Stratigraphic, Assessment Unit 20540101



Tanezzuft-Oued Mya Structural/Stratigraphic, Assessment Unit 20540101



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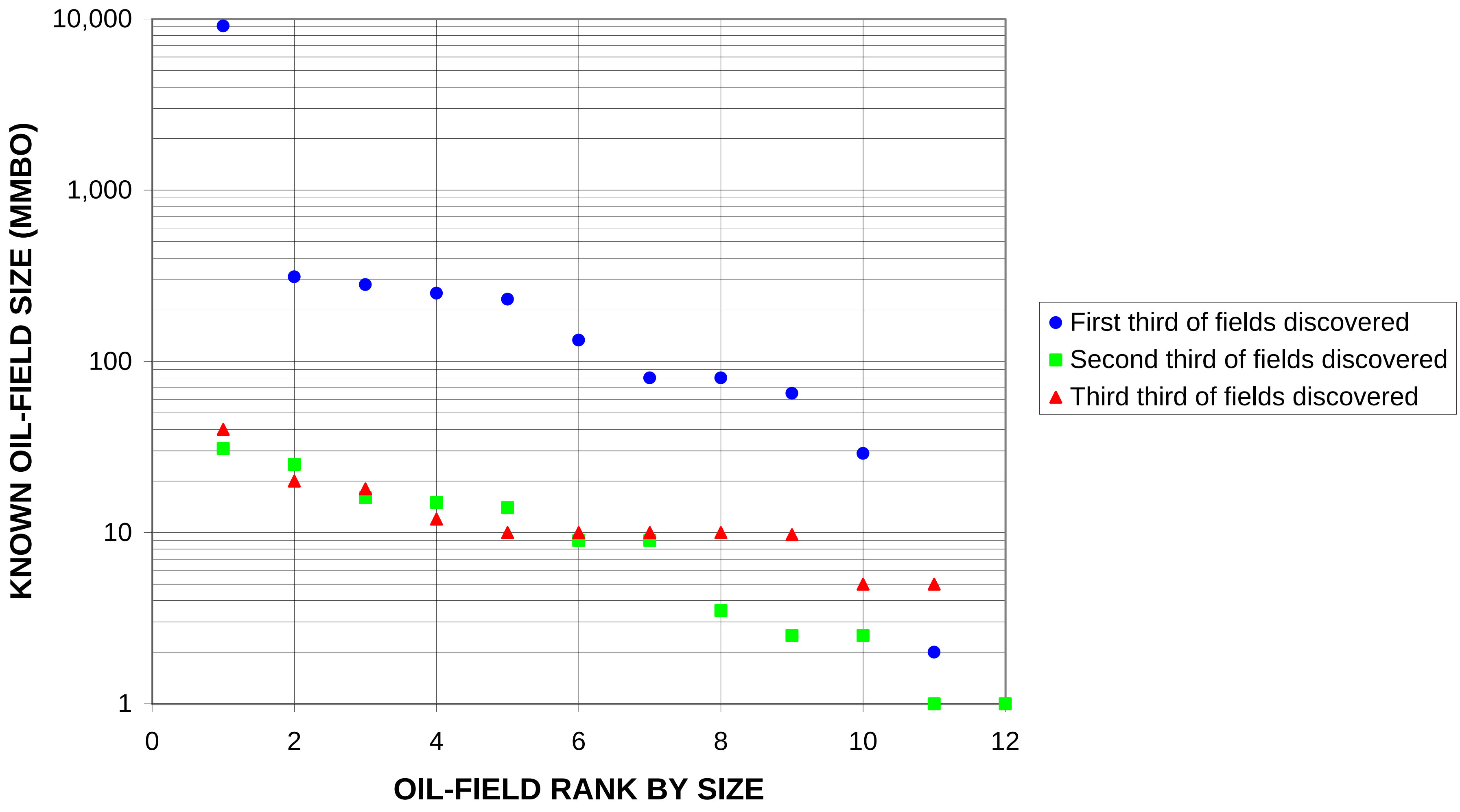
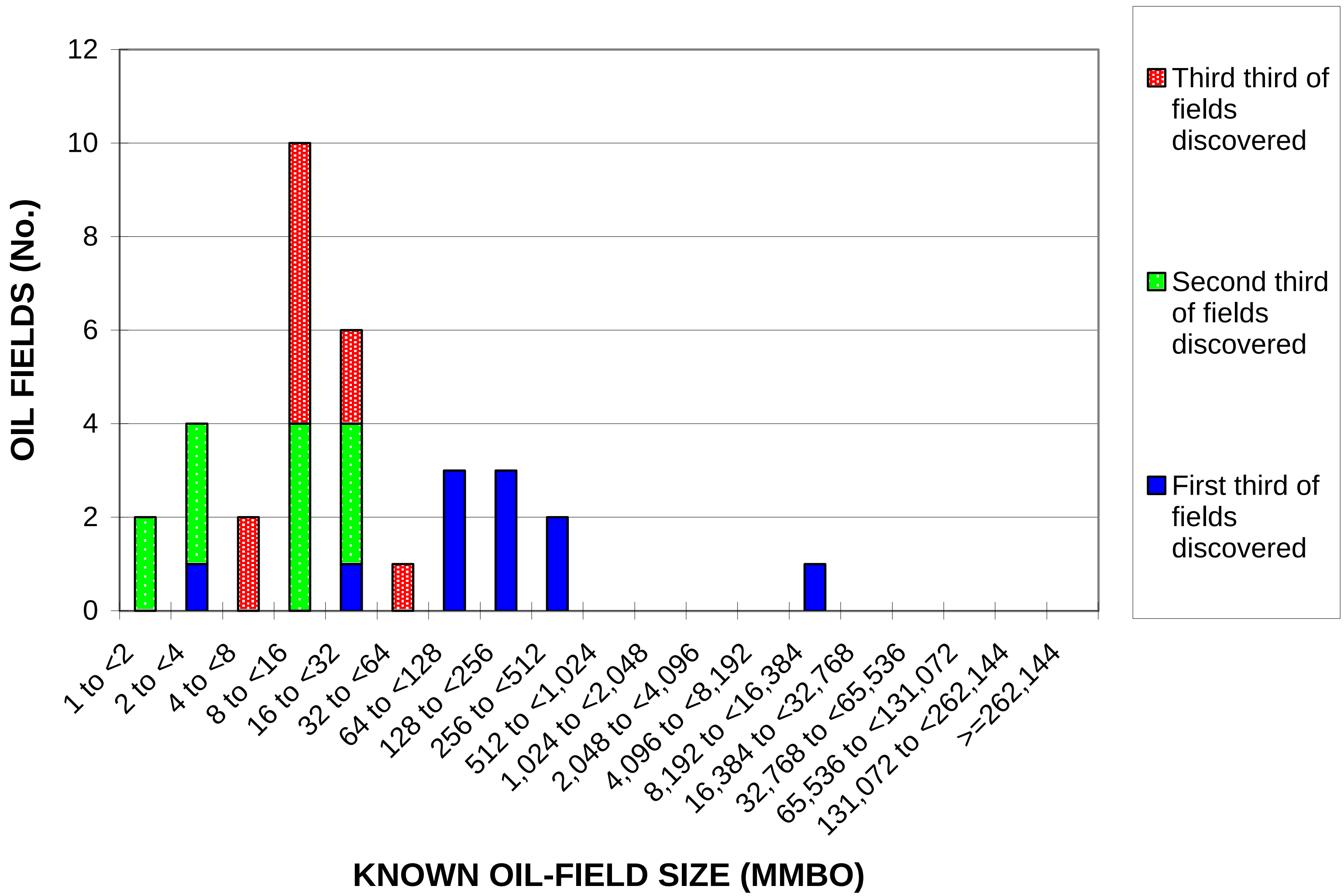


Tanezzuft-Oued Mya Structural/Stratigraphic, Assessment Unit 20540101



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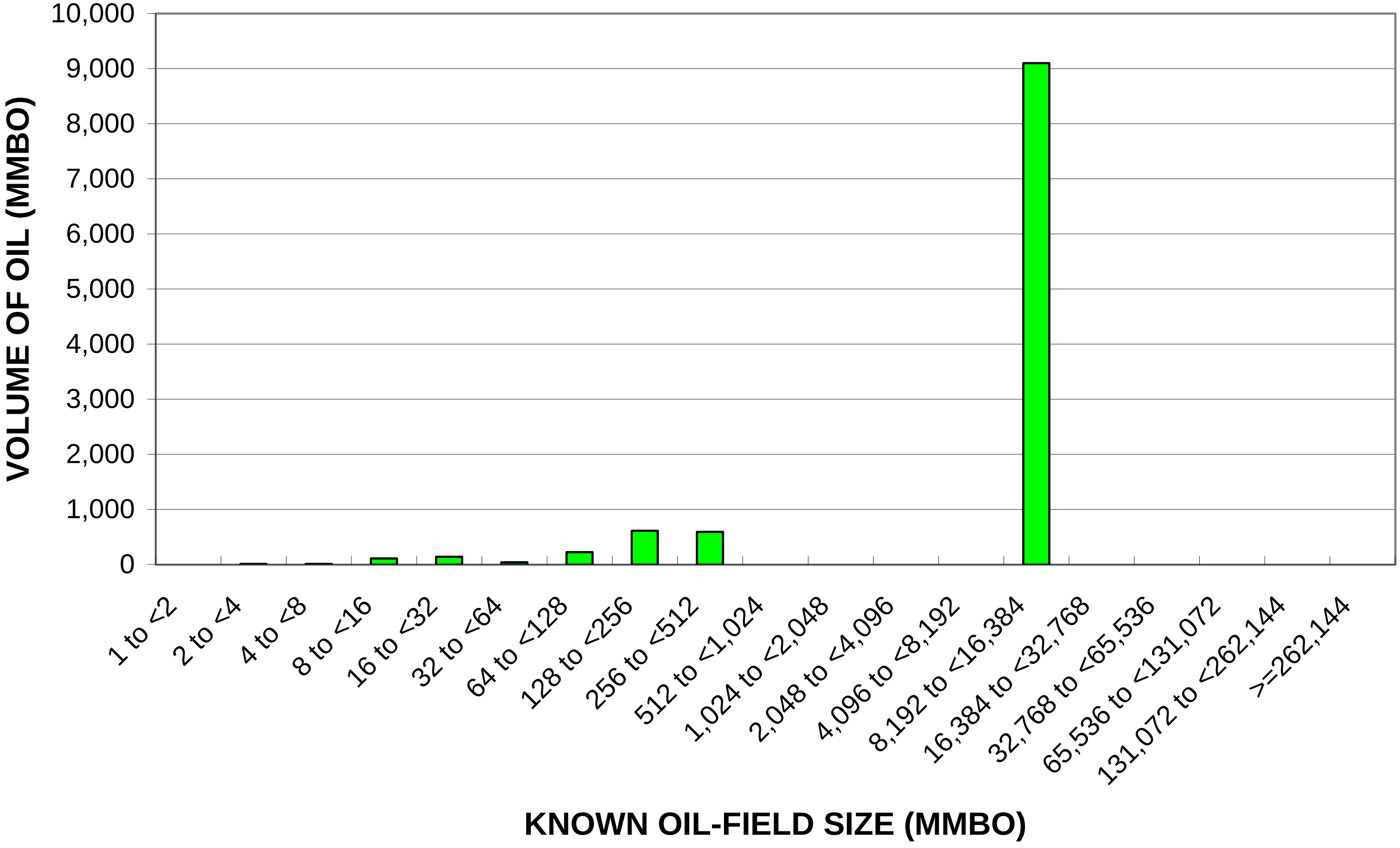

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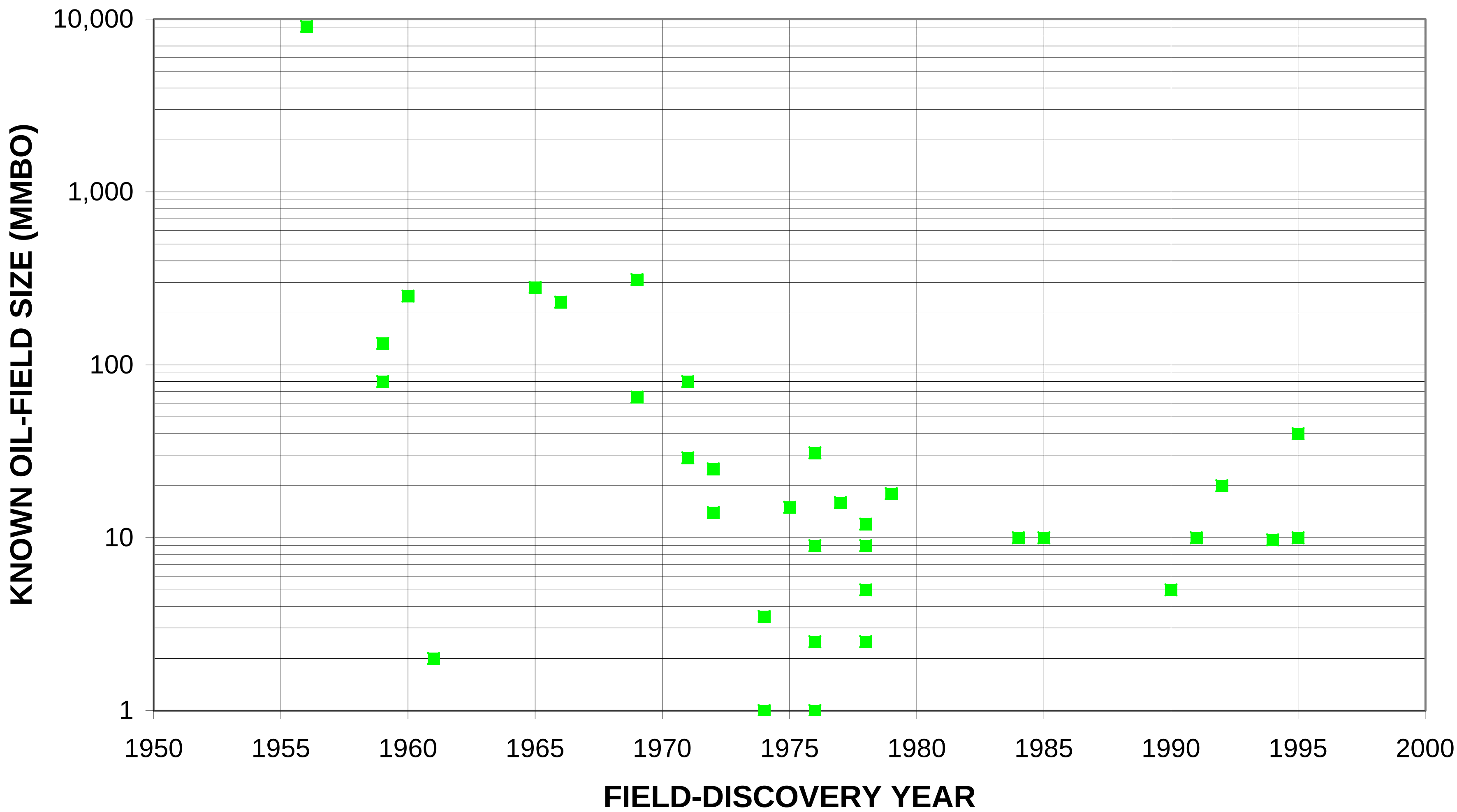

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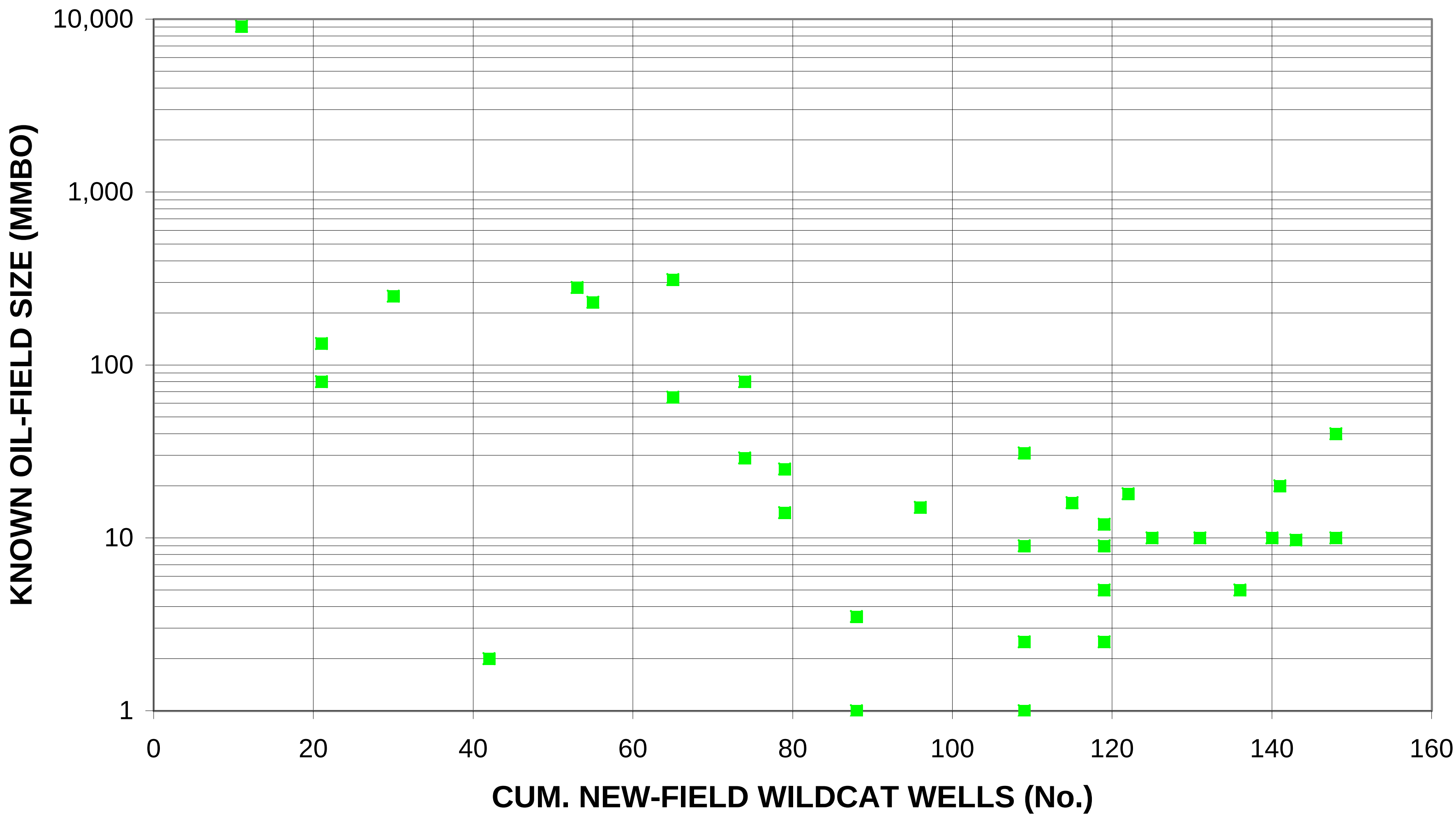

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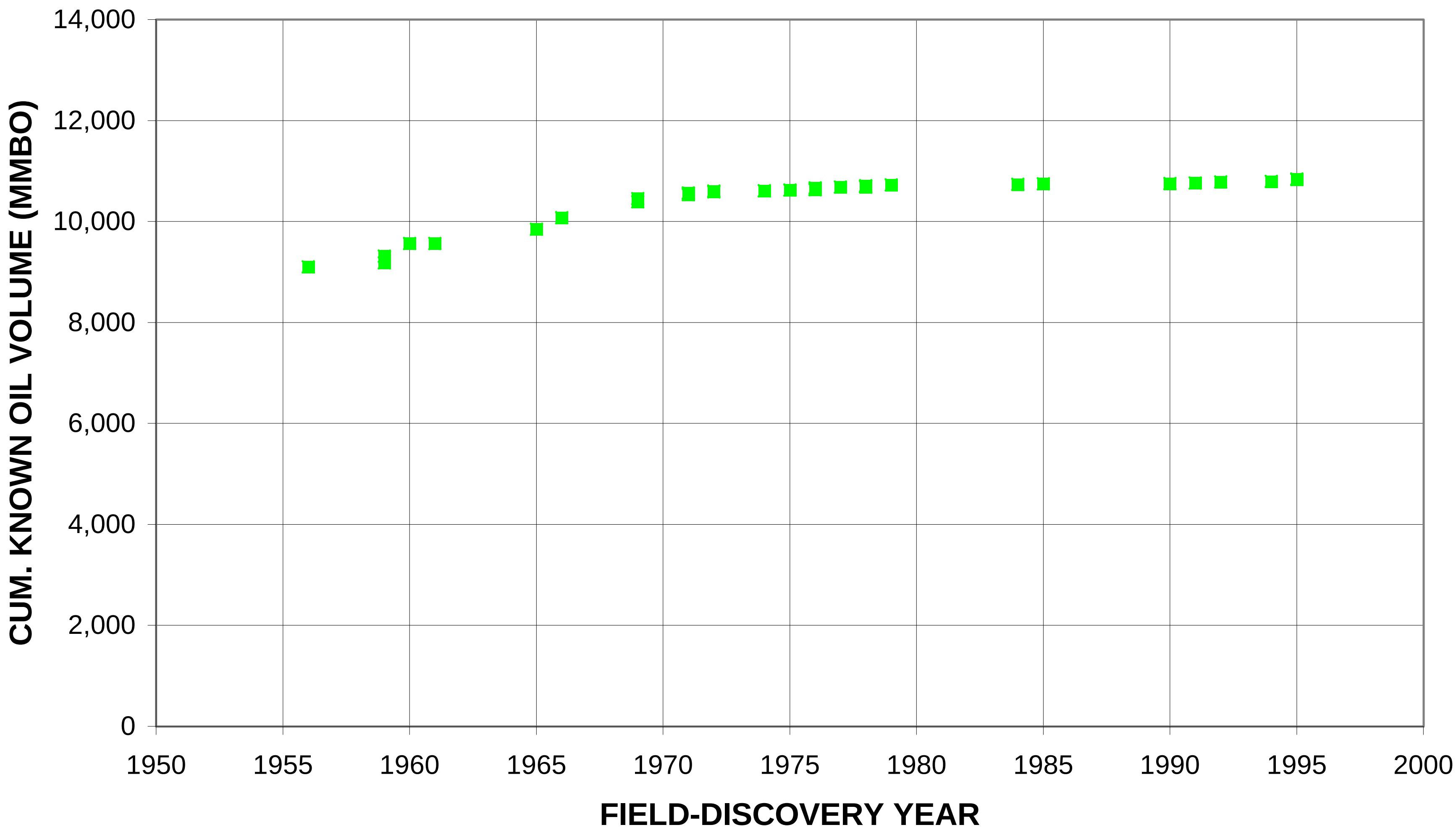

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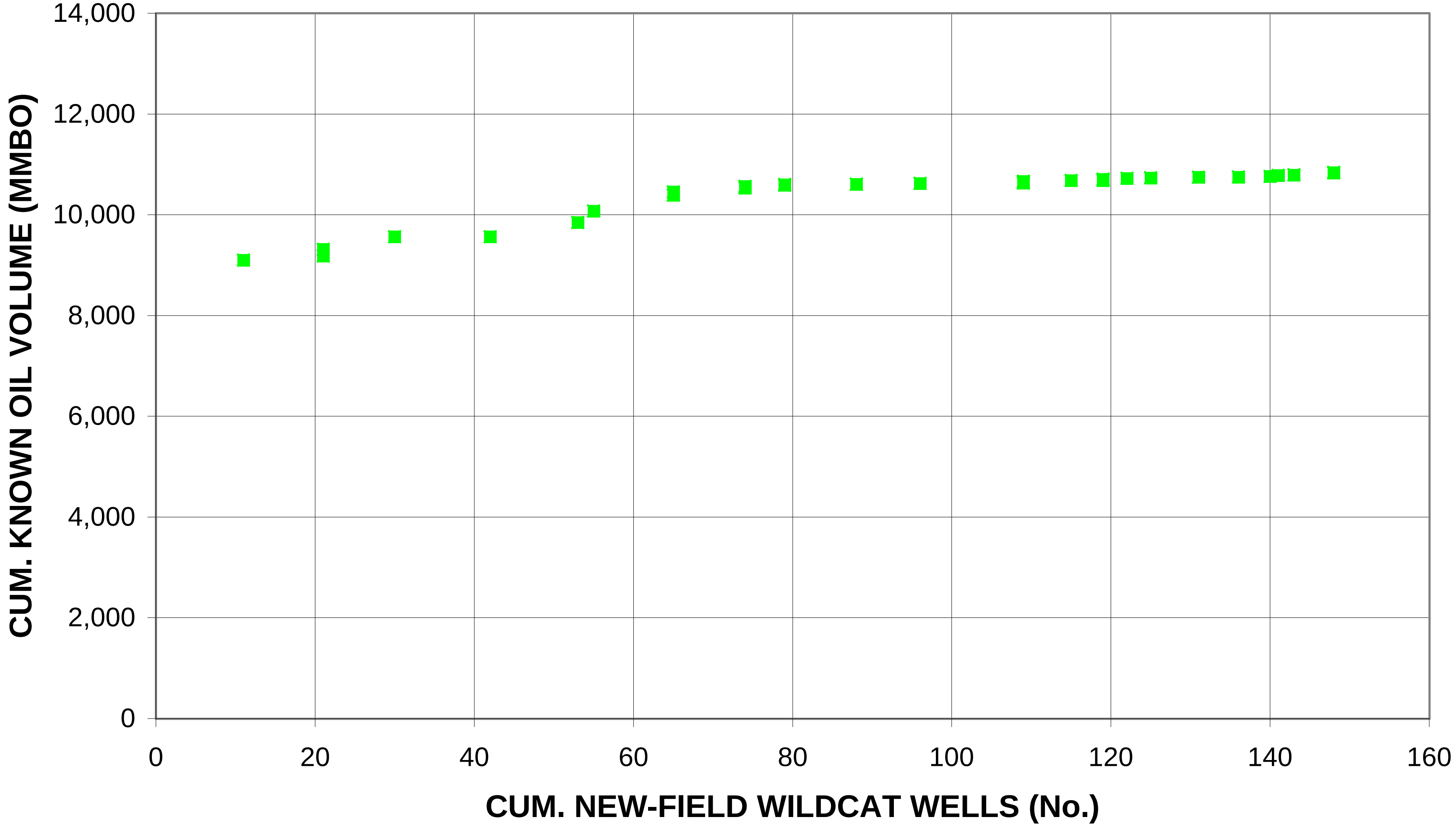

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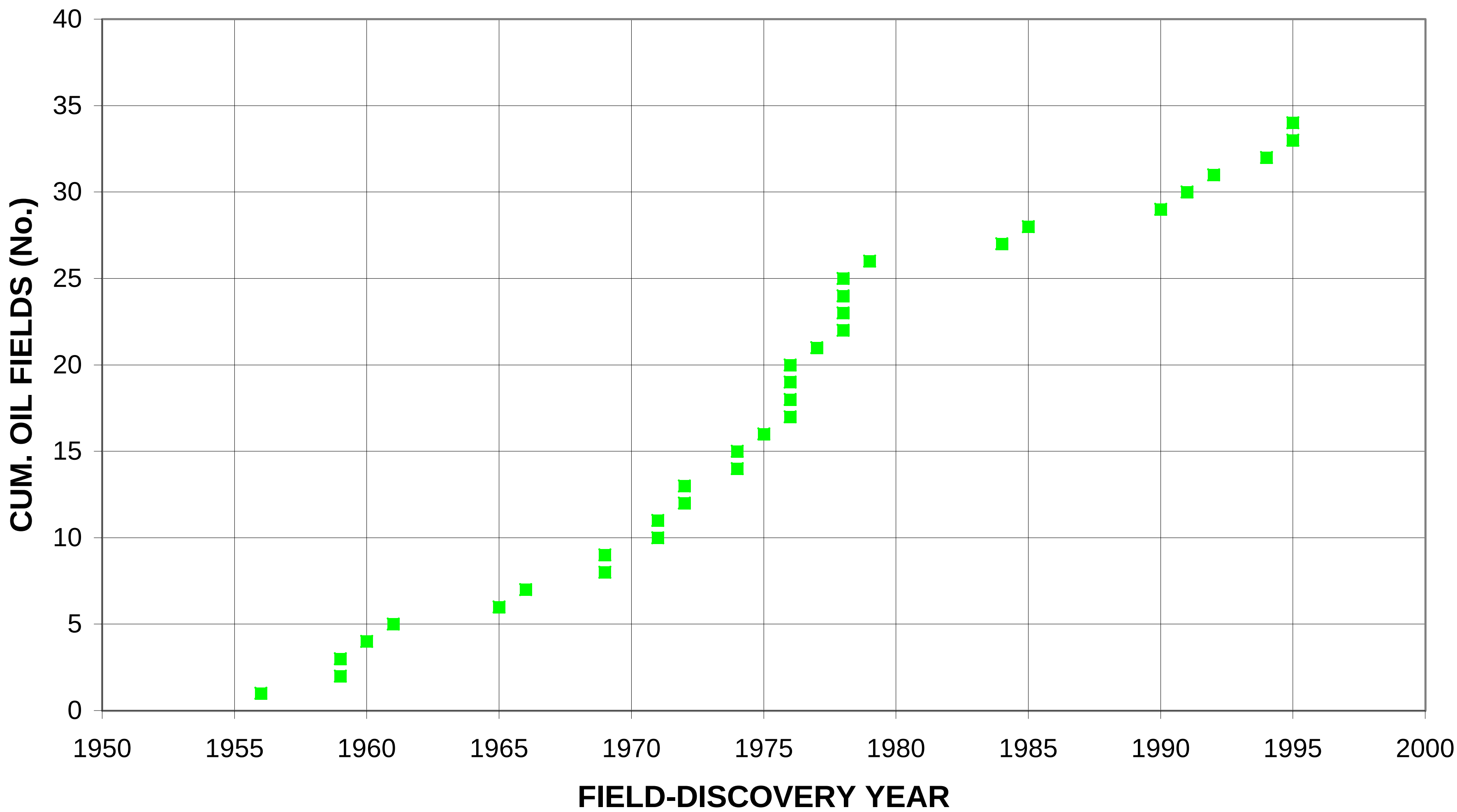

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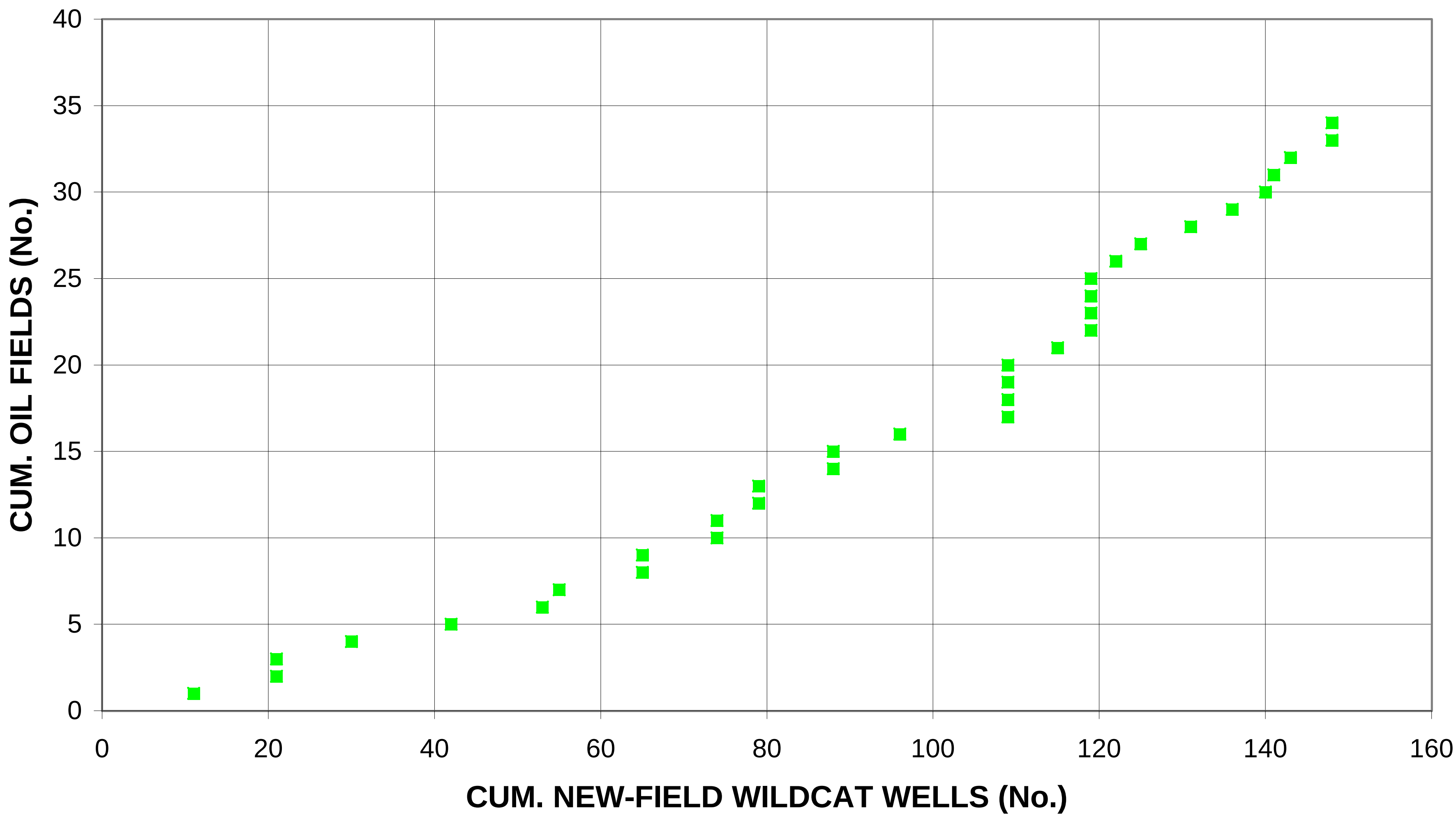

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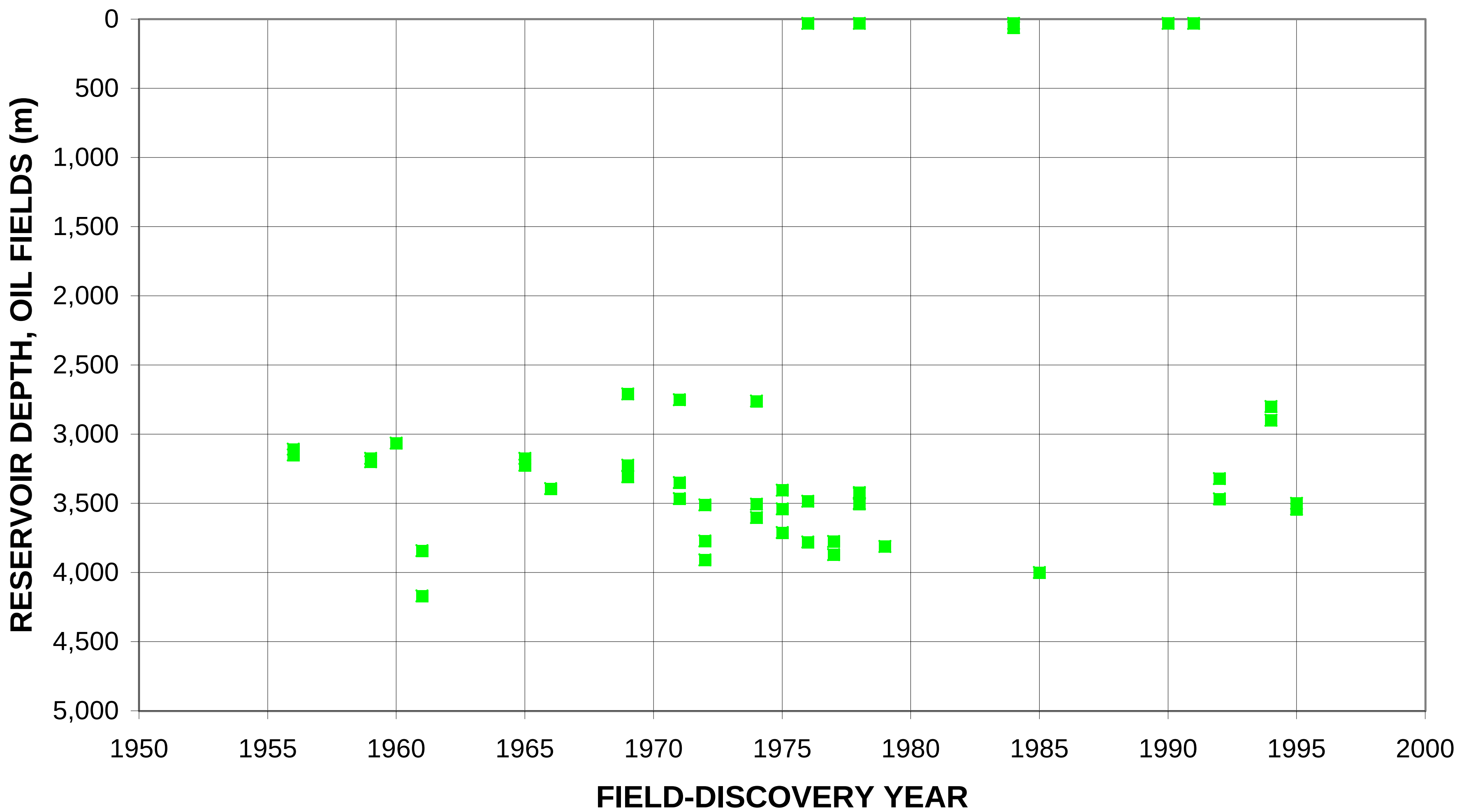

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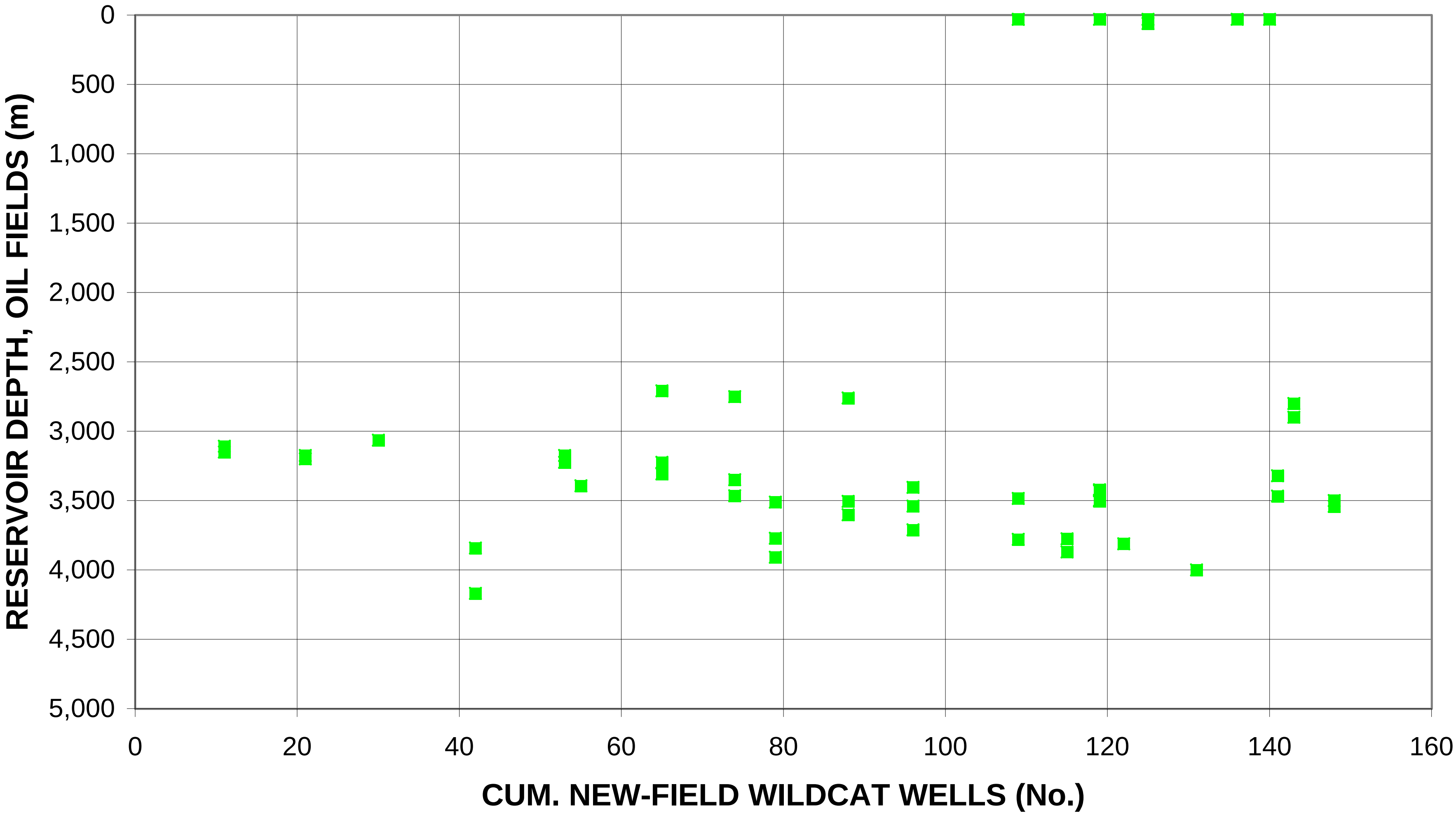
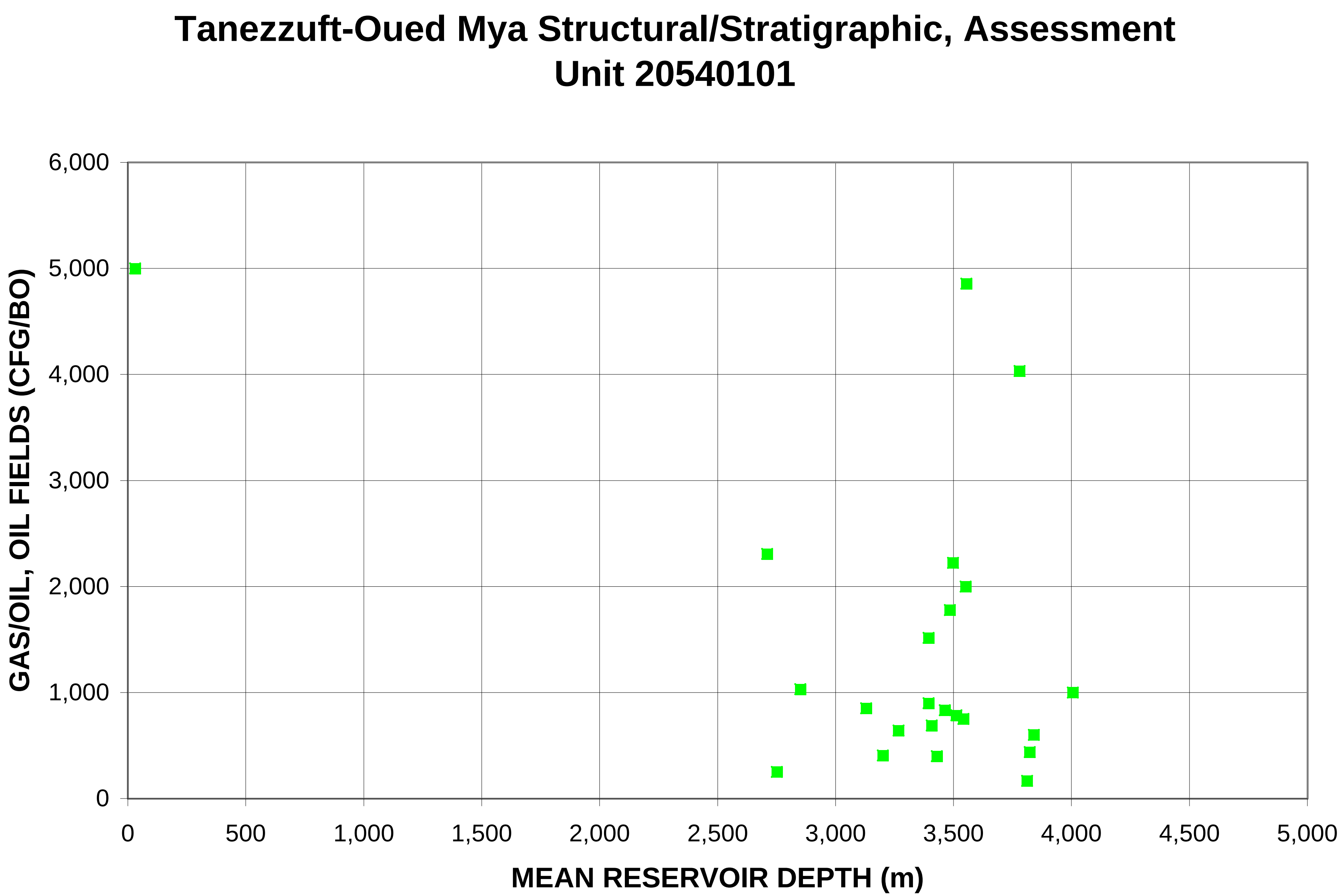
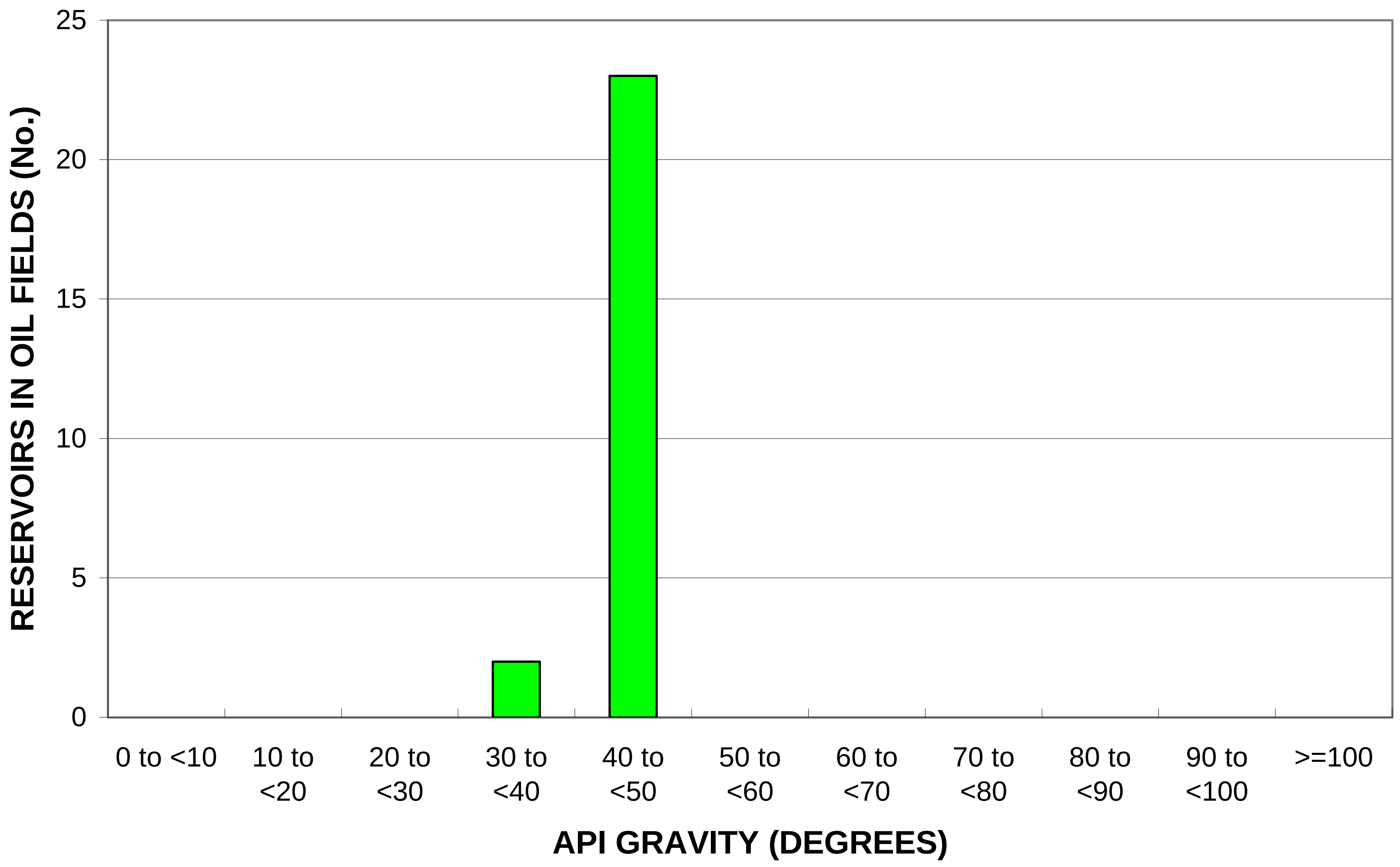



Tanezzuft-Oued Mya Structural/Stratigraphic, Assessment Unit 20540101
GAS/OIL, OIL FIELDS (CFG/BO)
MEAN RESERVOIR DEPTH (m)
0
1,000
2,000
3,000
4,000
5,000
6,000
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000

Tanezzuft-Oued Mya Structural/Stratigraphic, Assessment Unit 20540101



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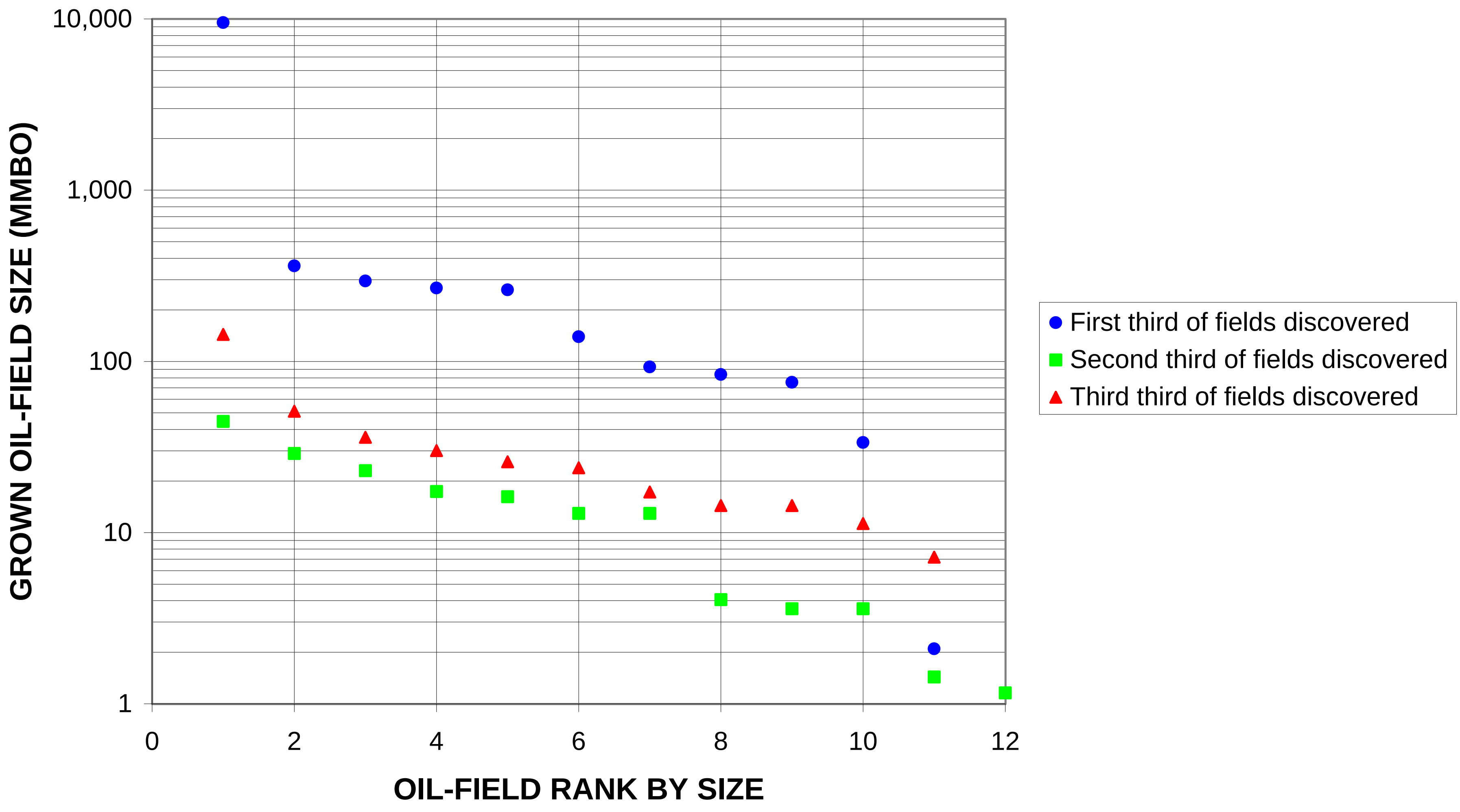

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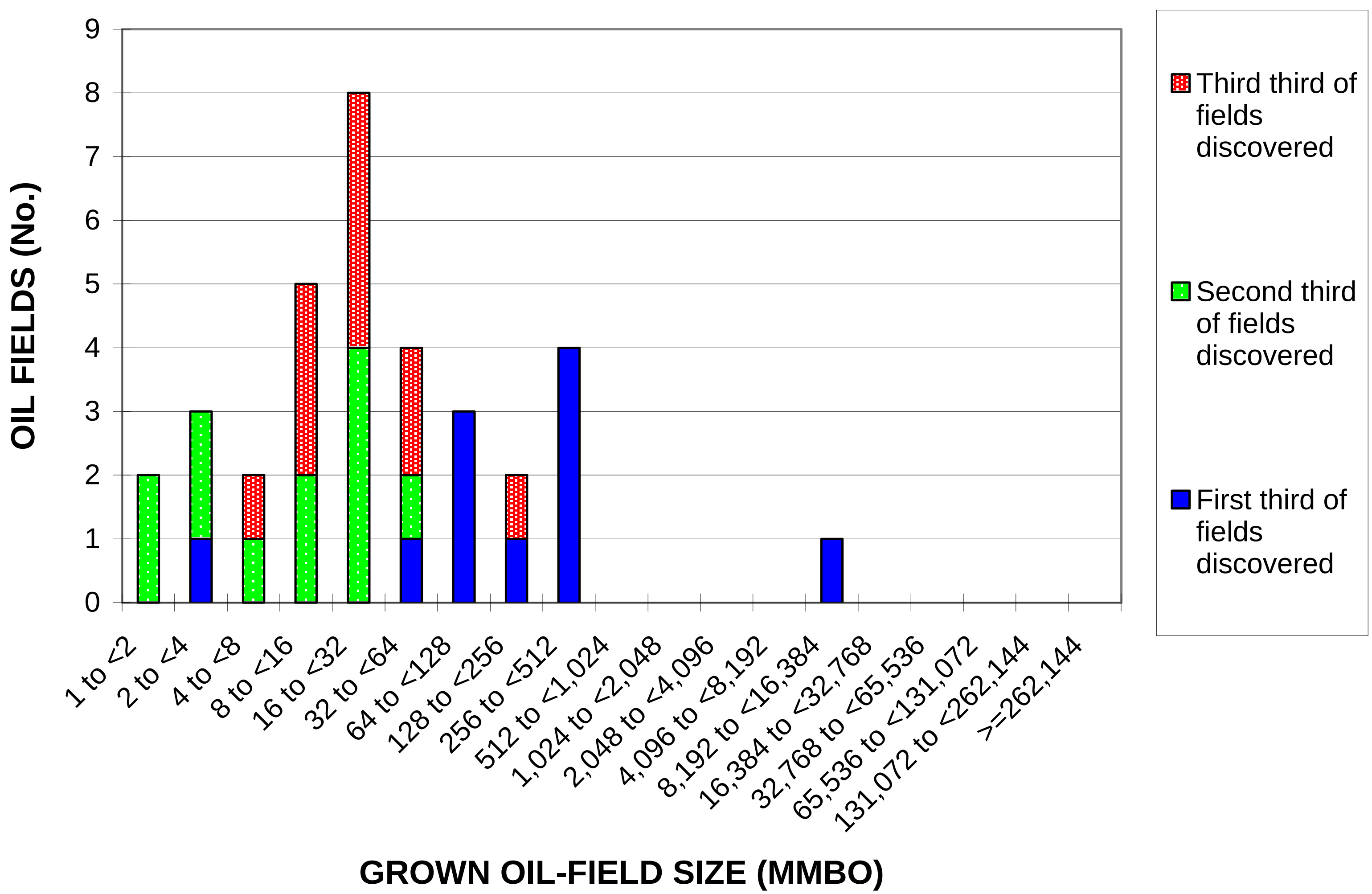

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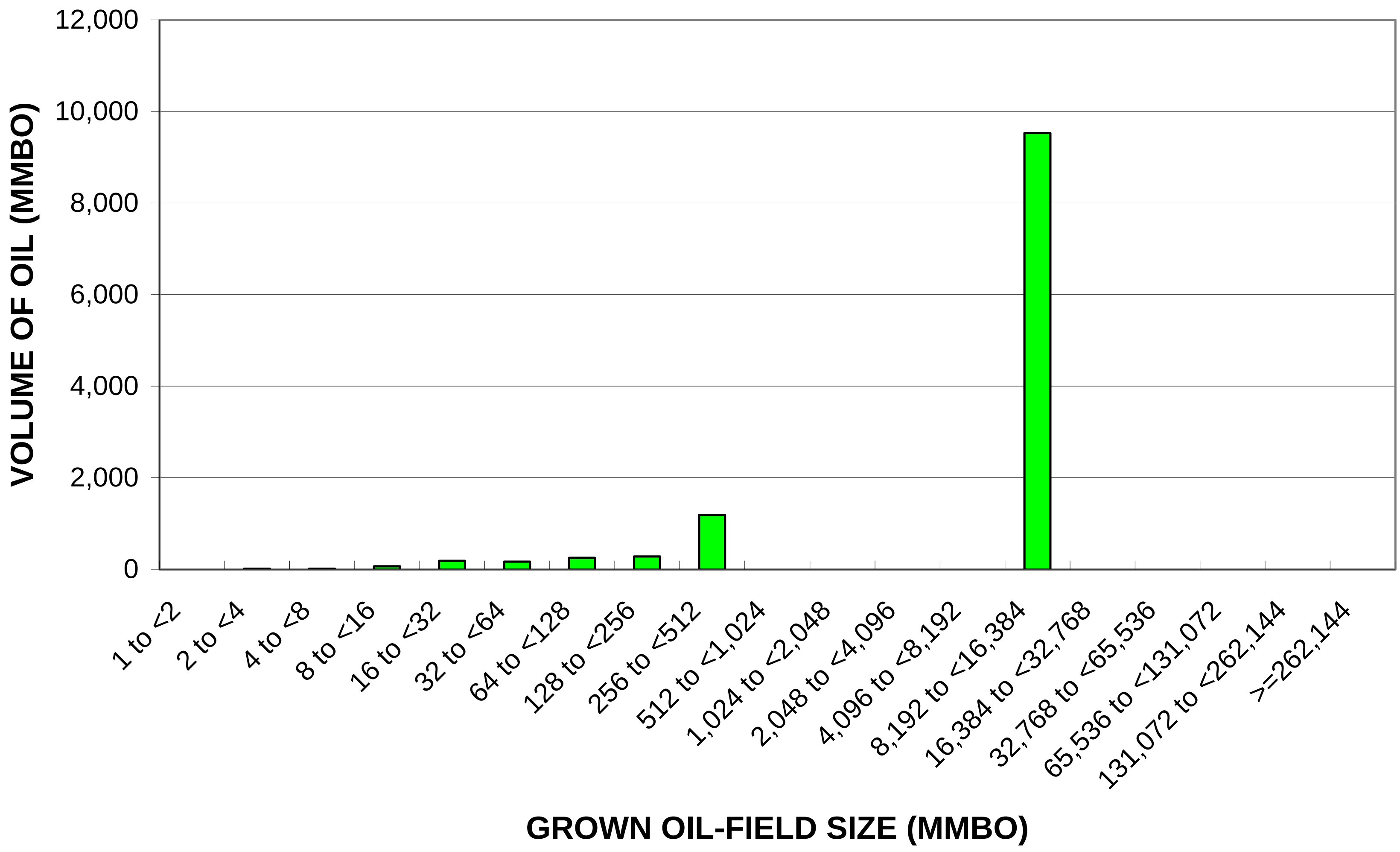

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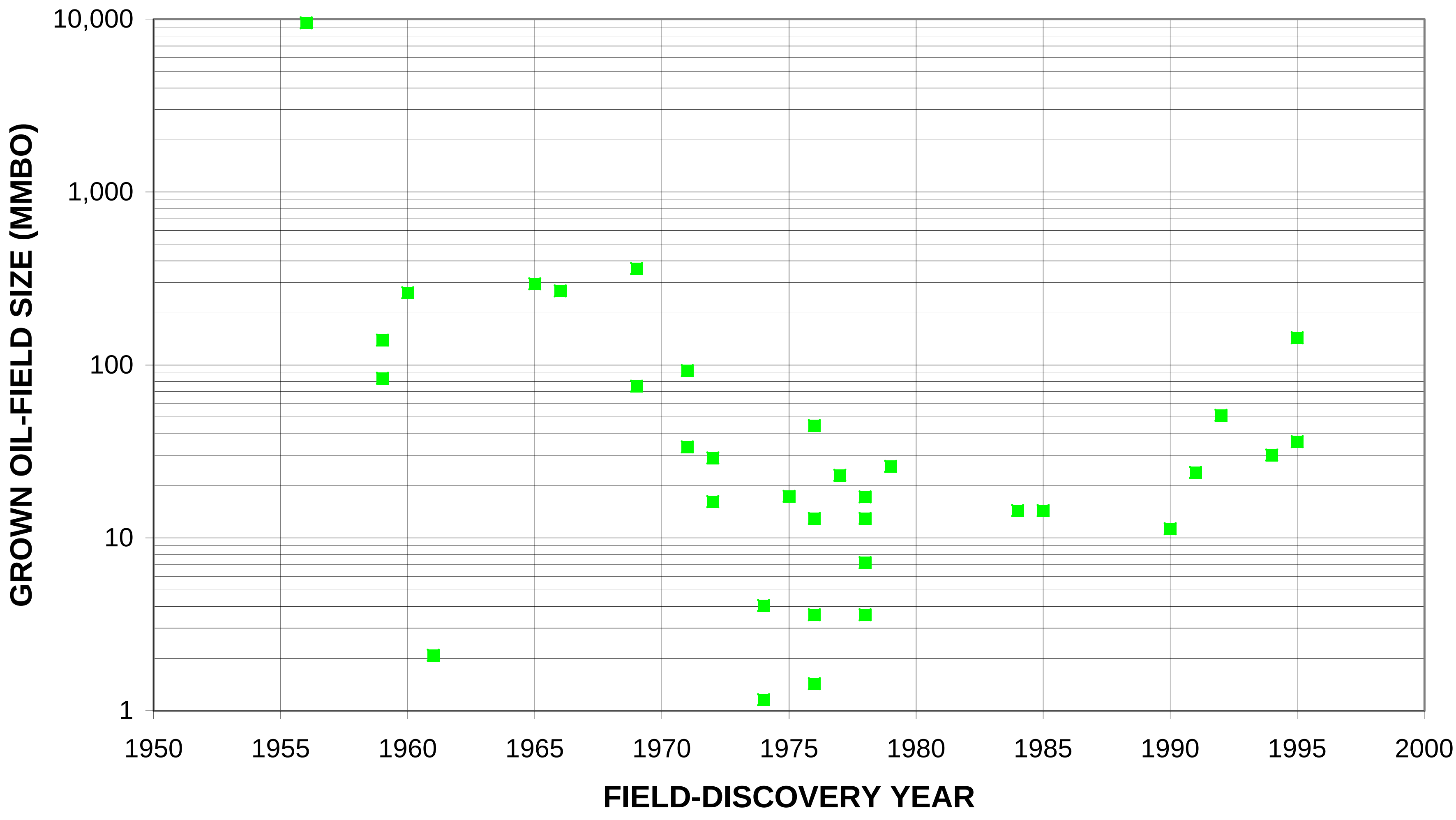

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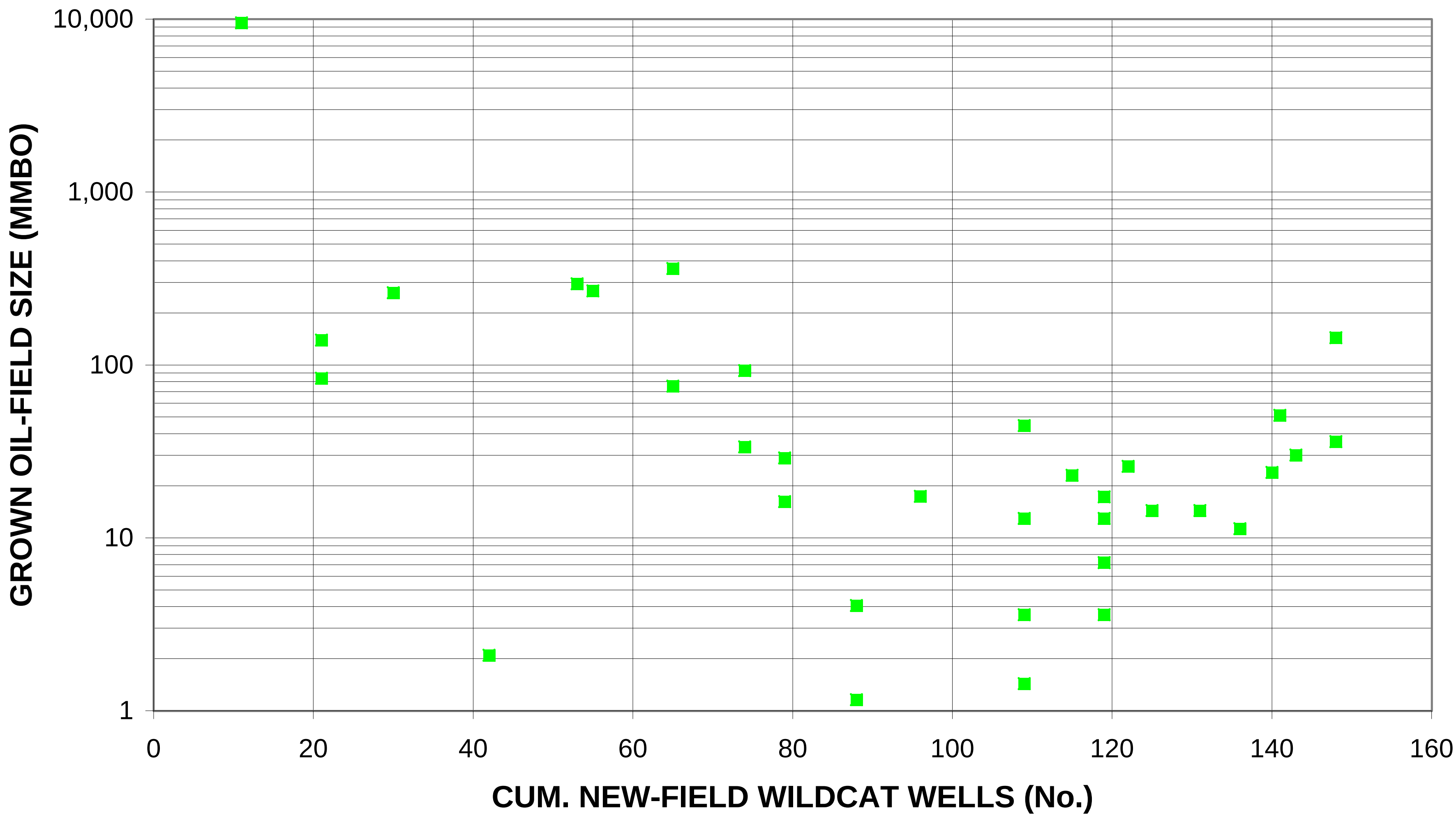

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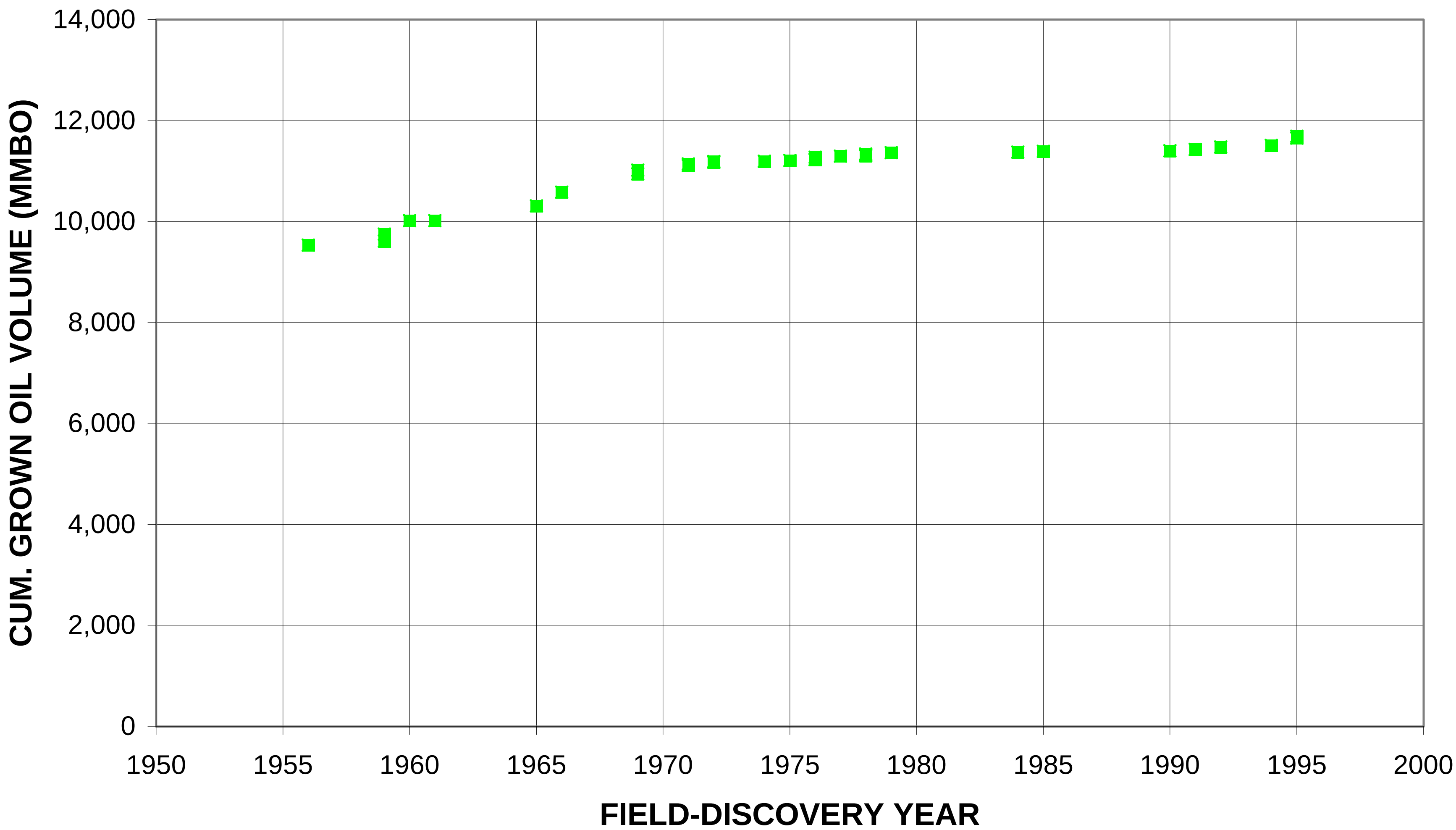

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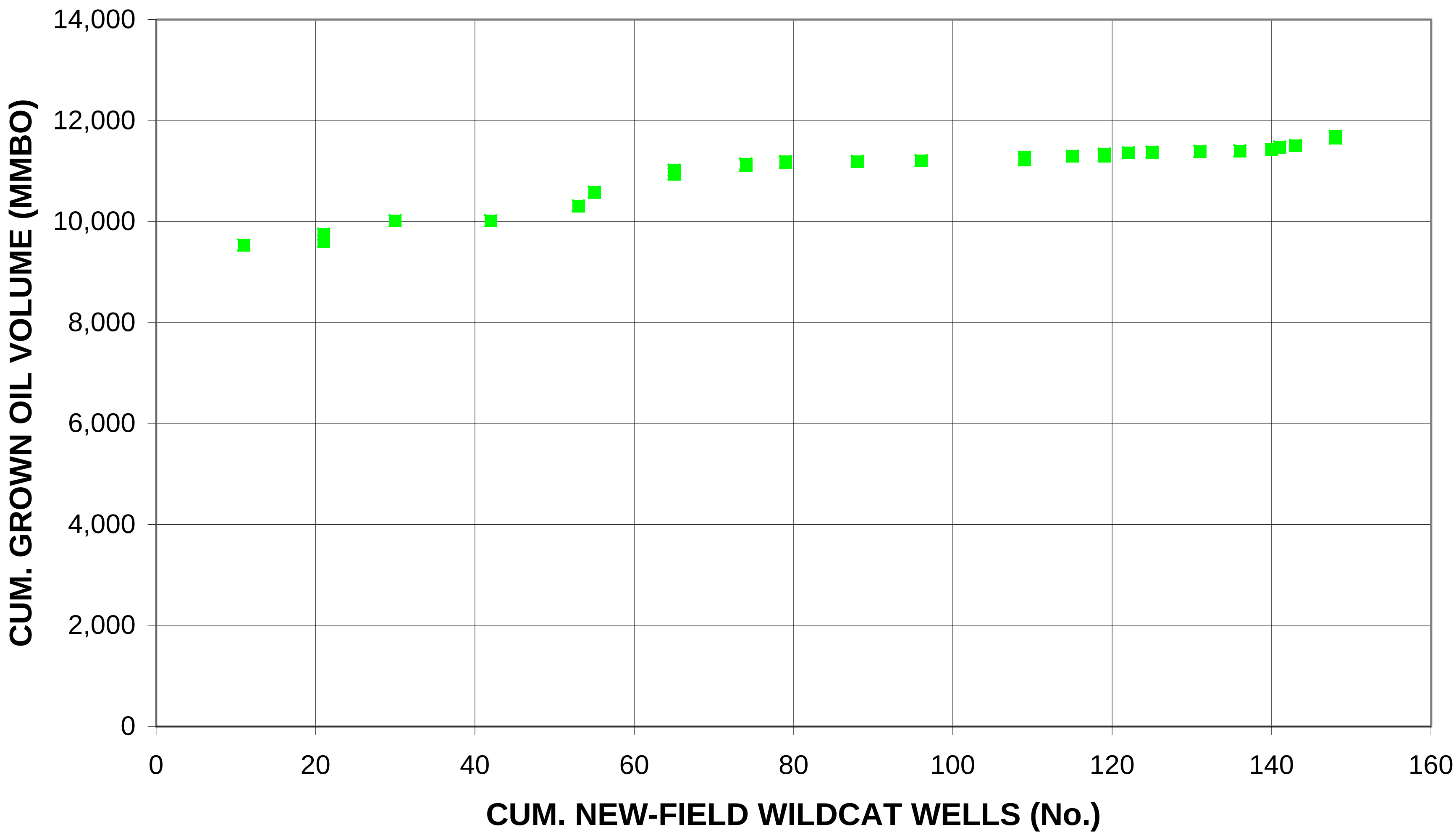

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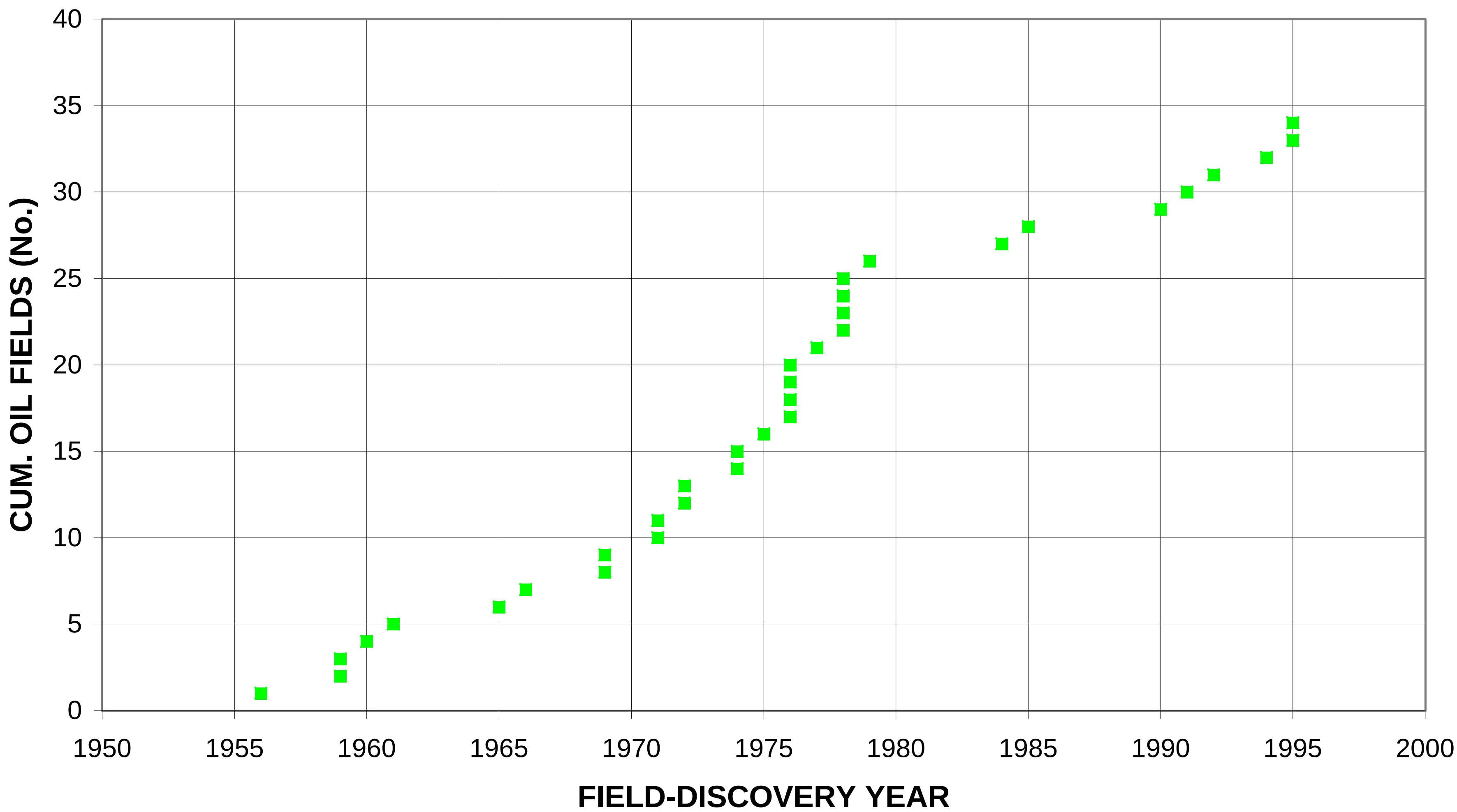

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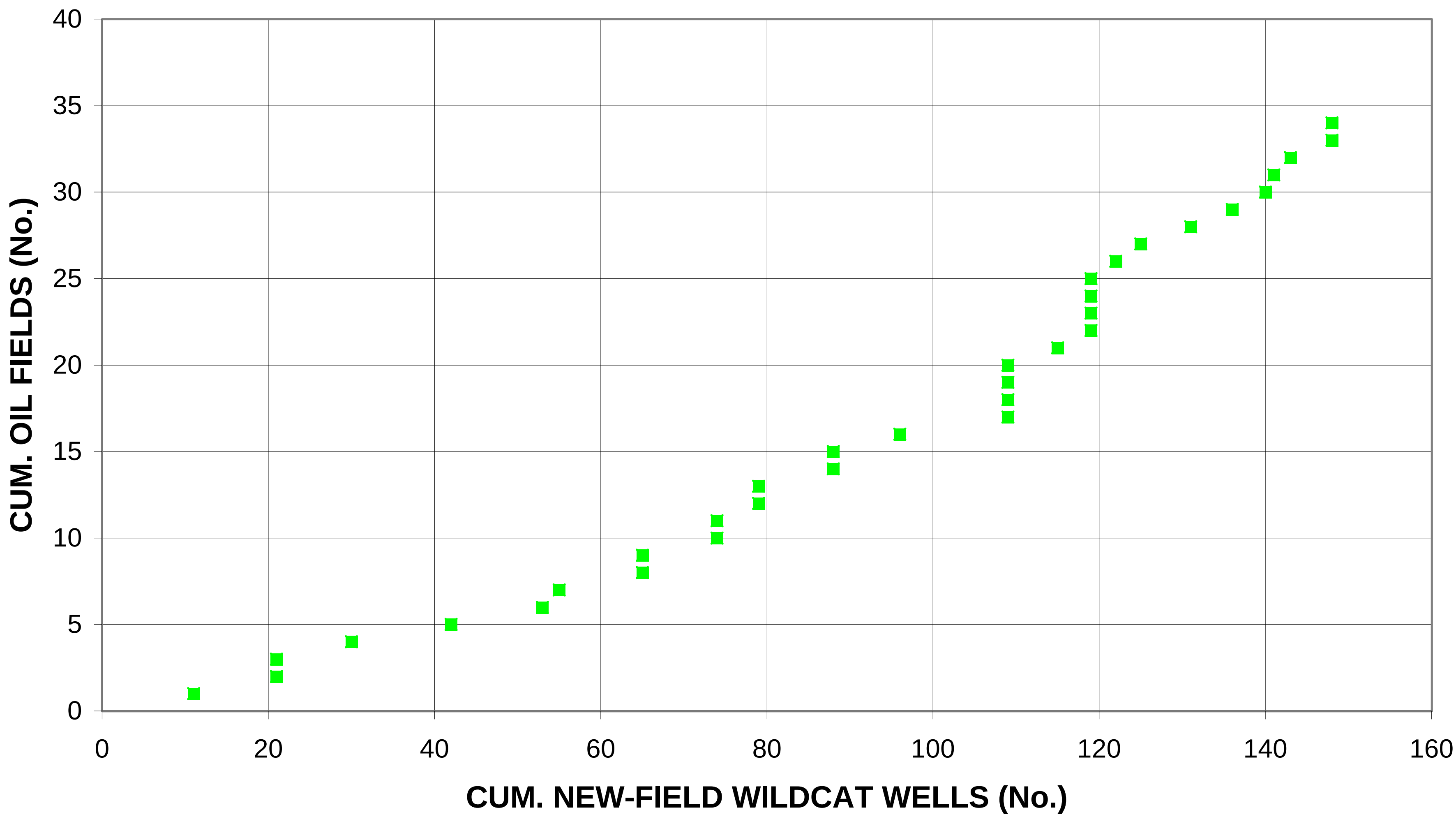

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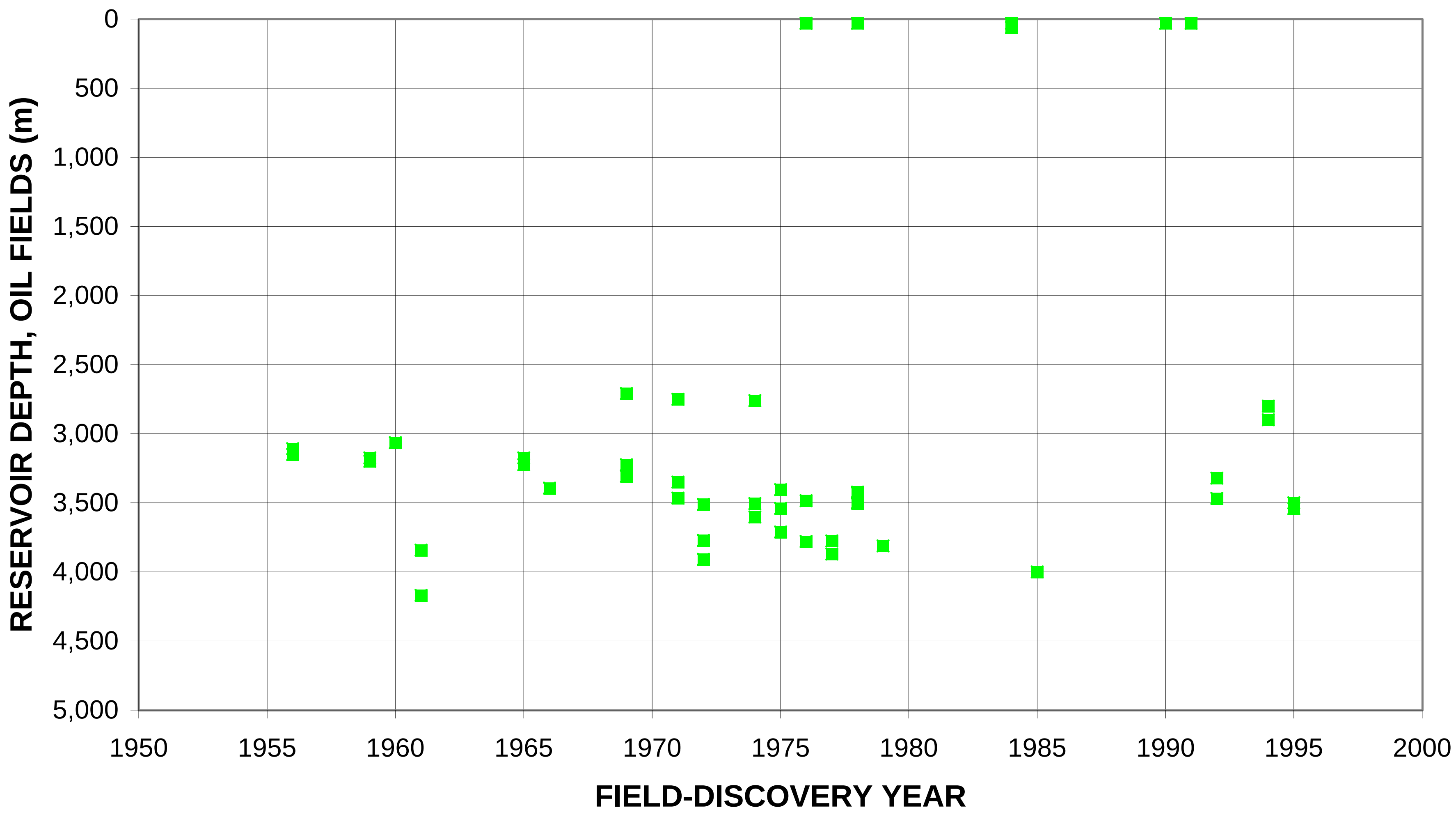

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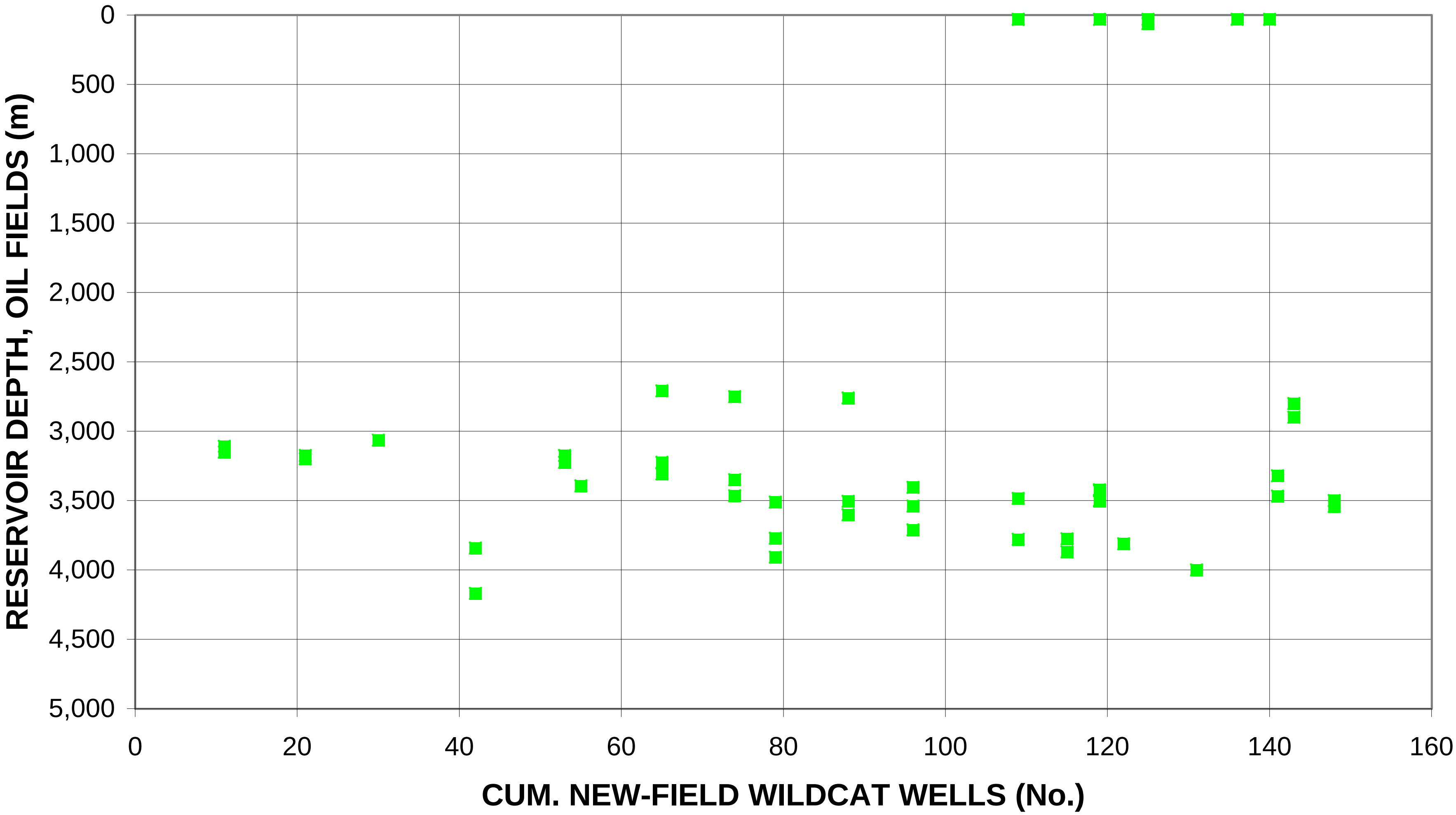

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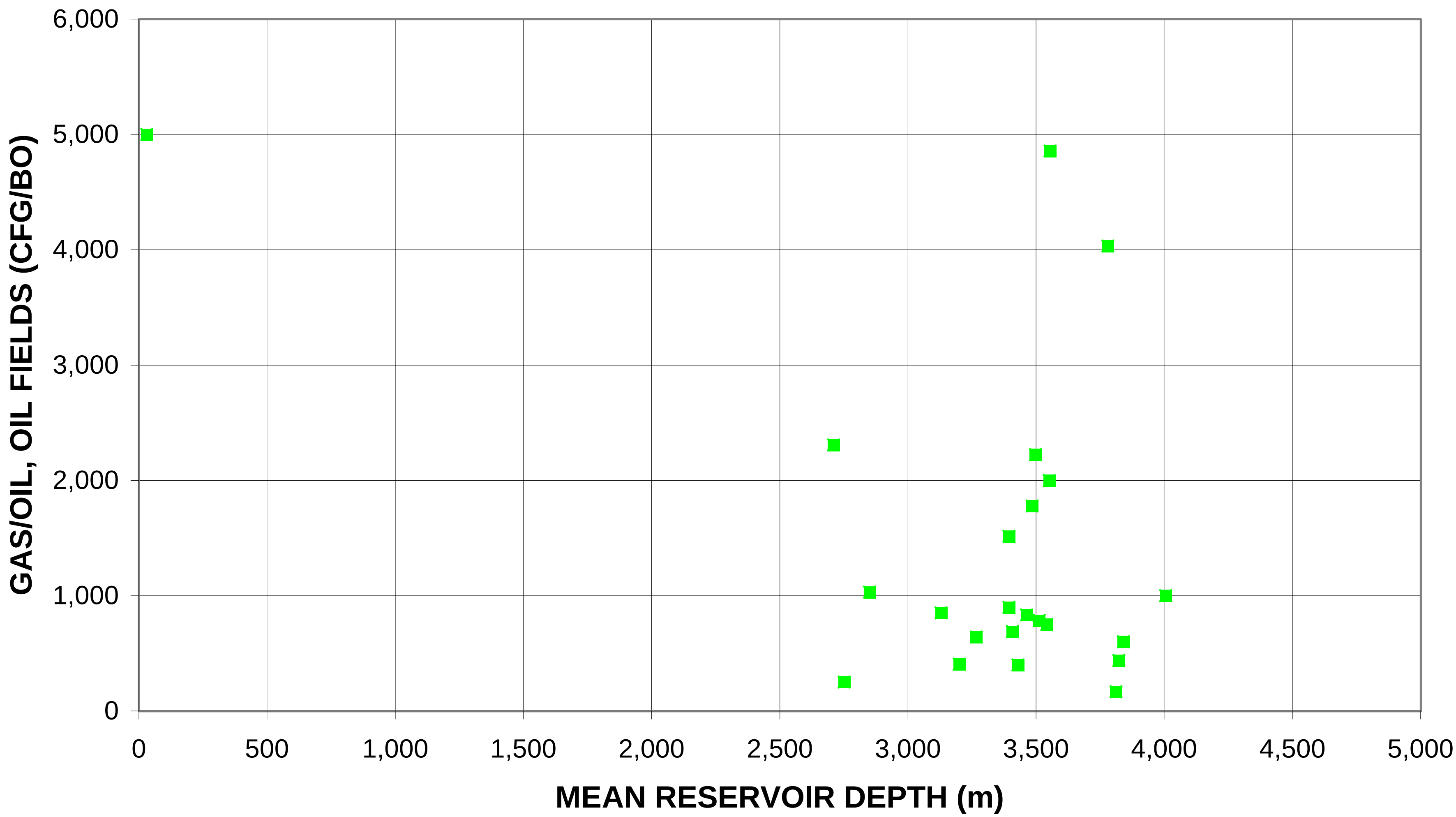

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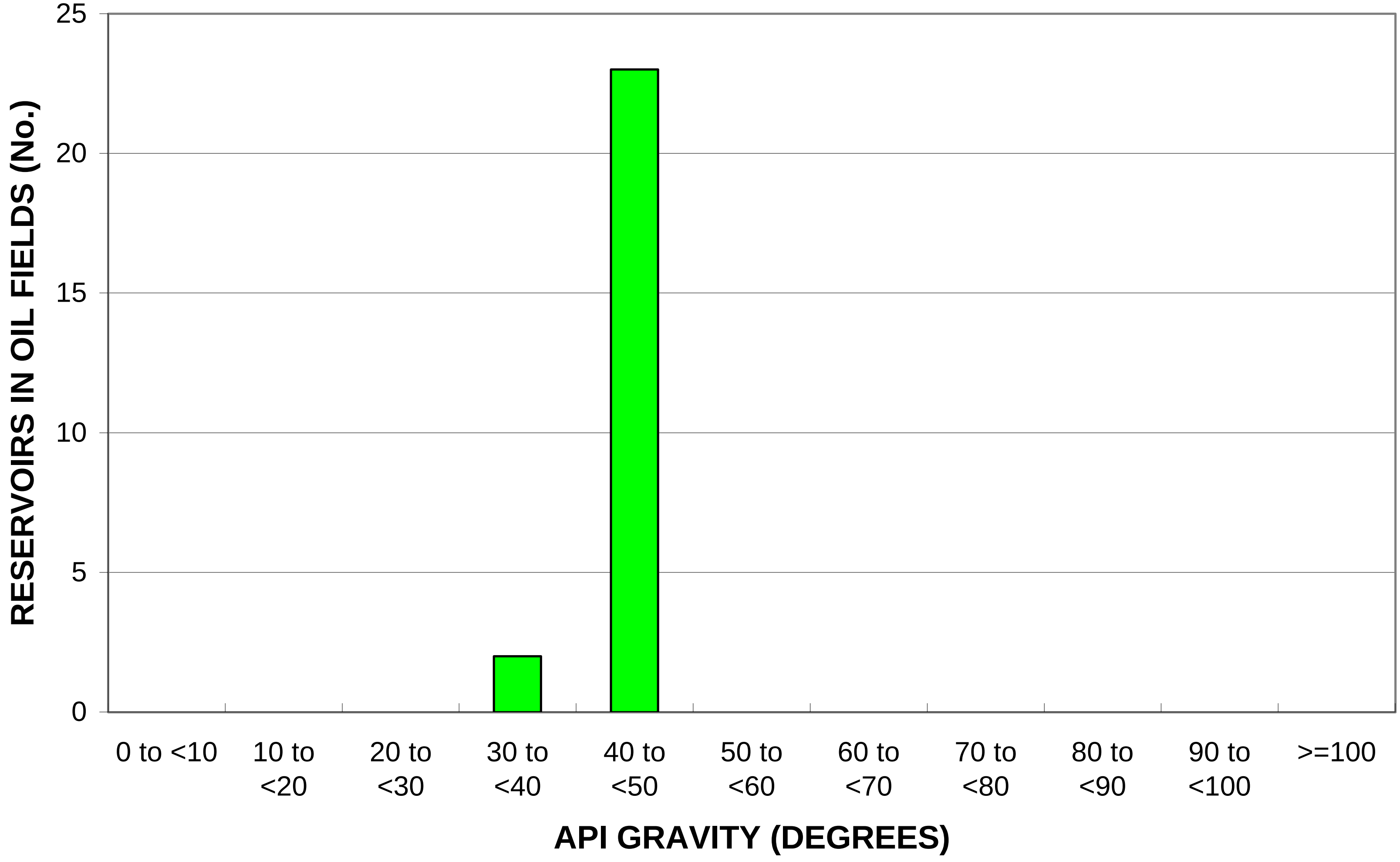
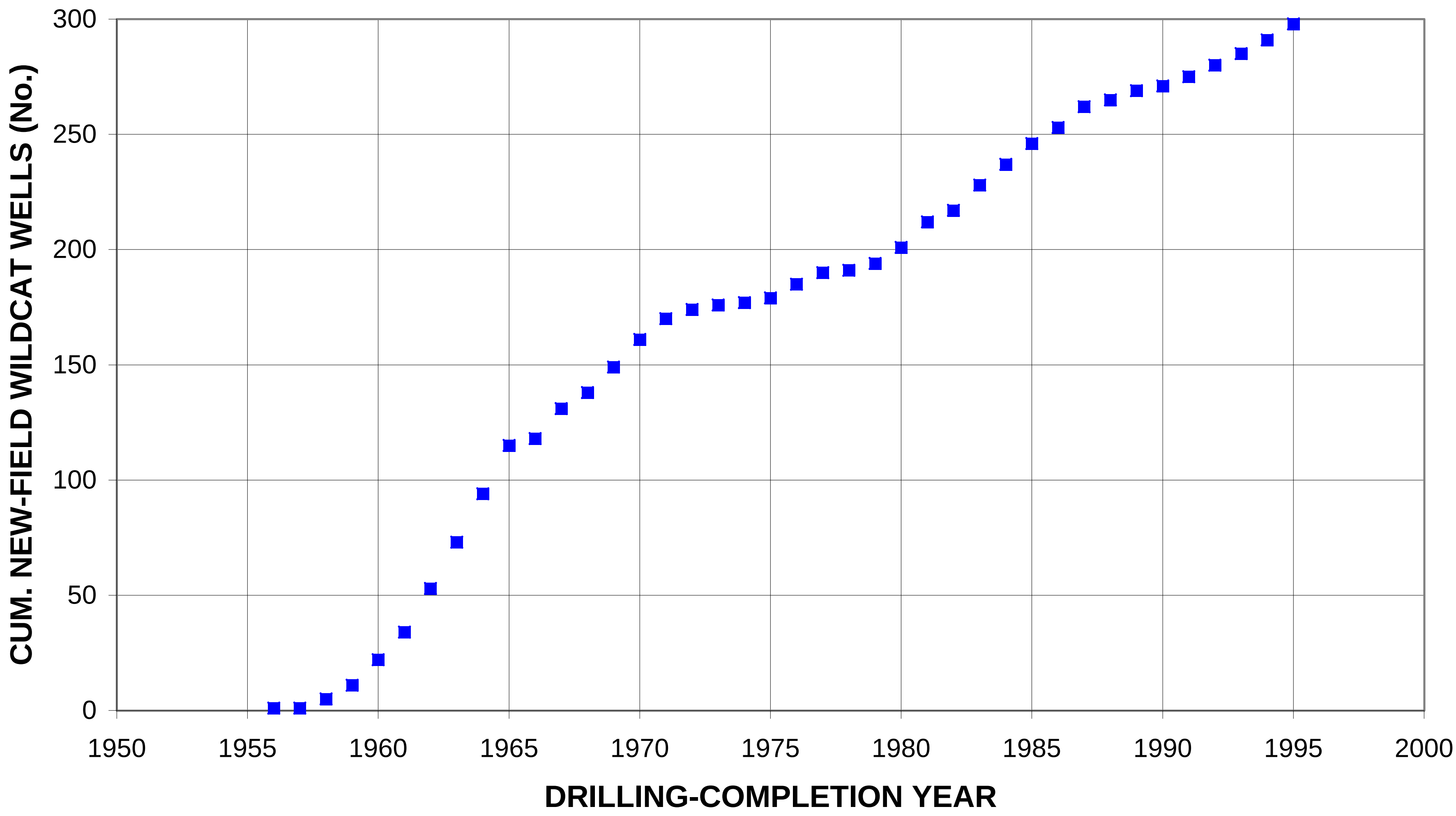
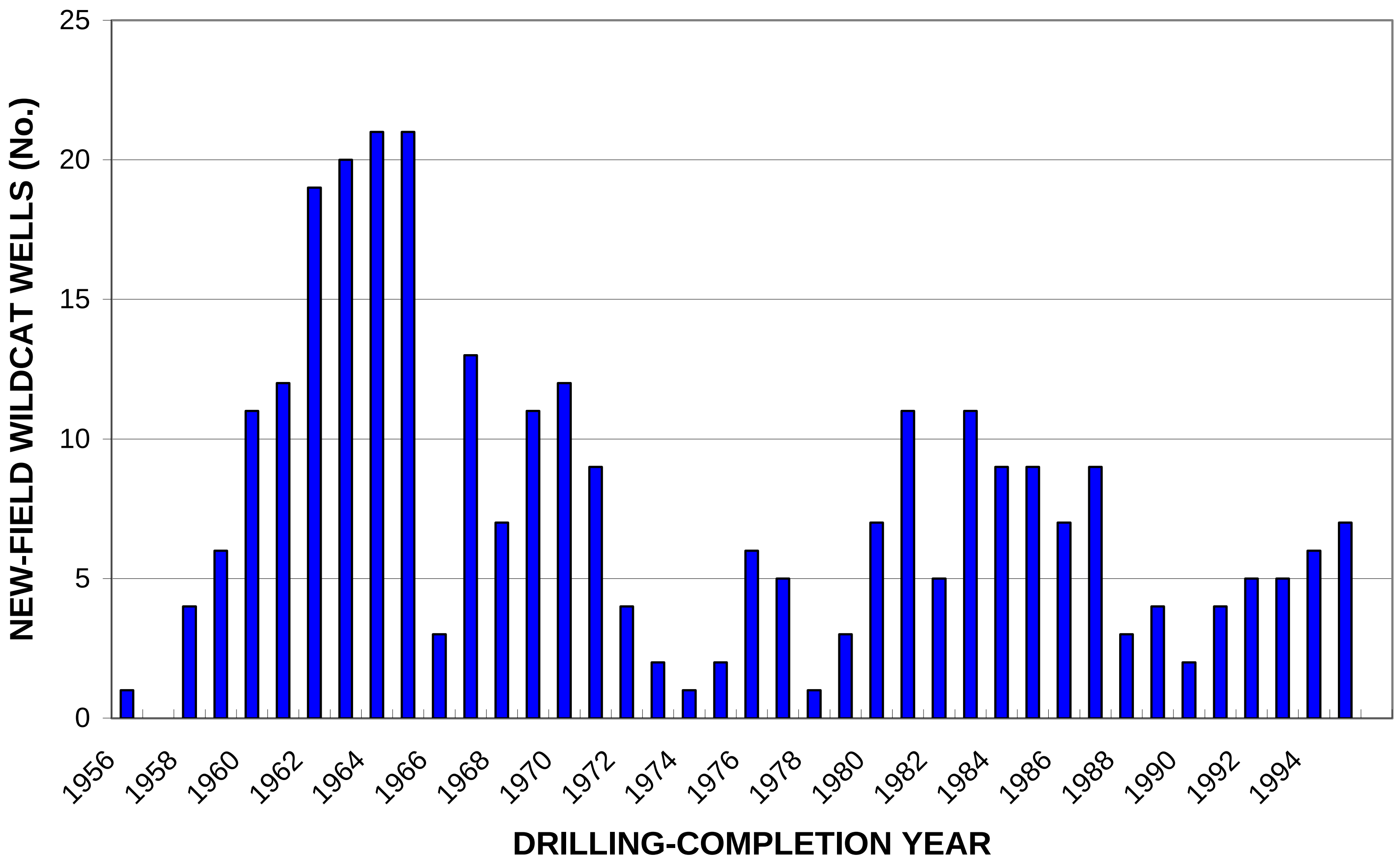


Appendix 2. Exploration-activity and discovery-history plots for the Tanezzuft-Ghadames Structural/Stratigraphic Assessment Unit.

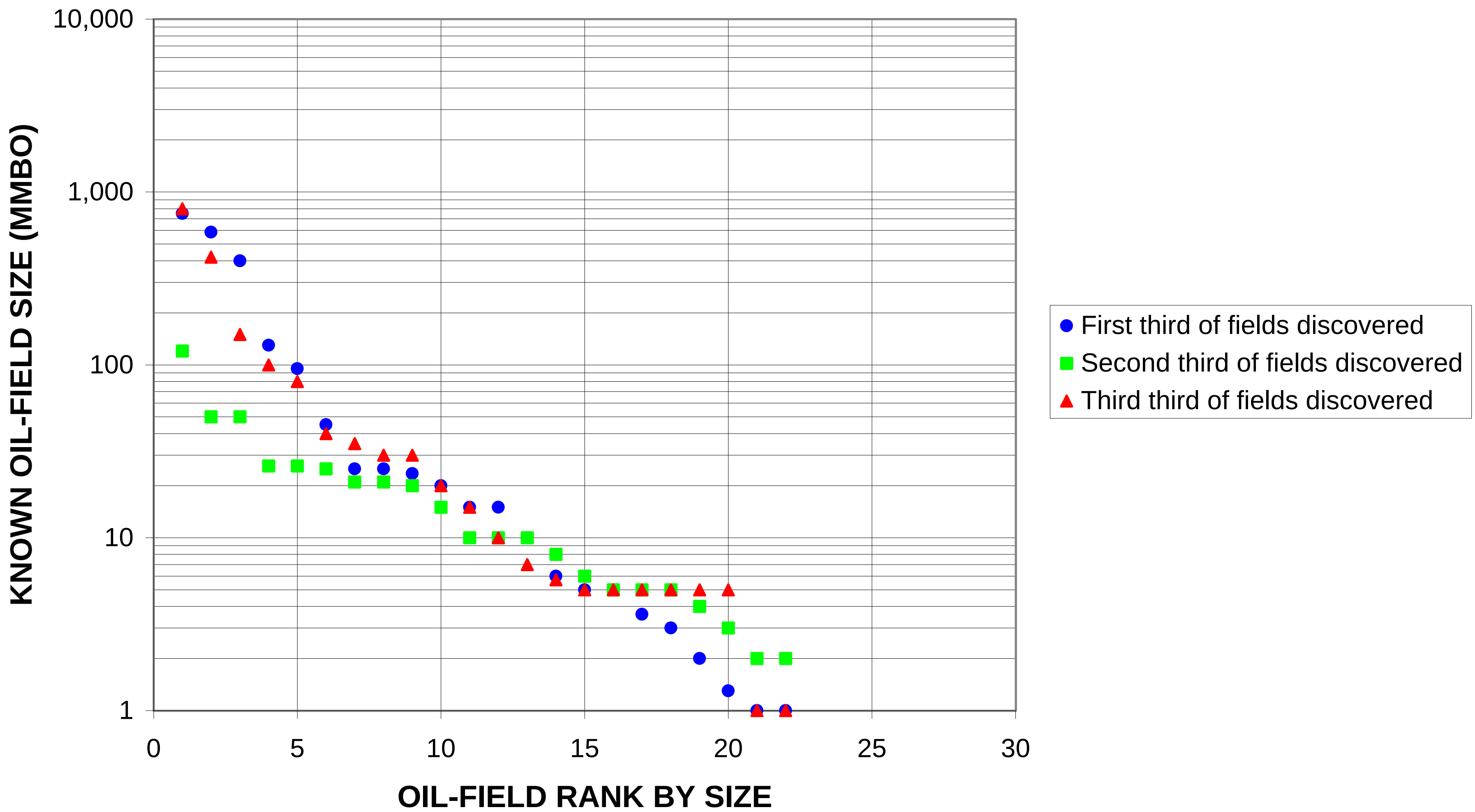
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



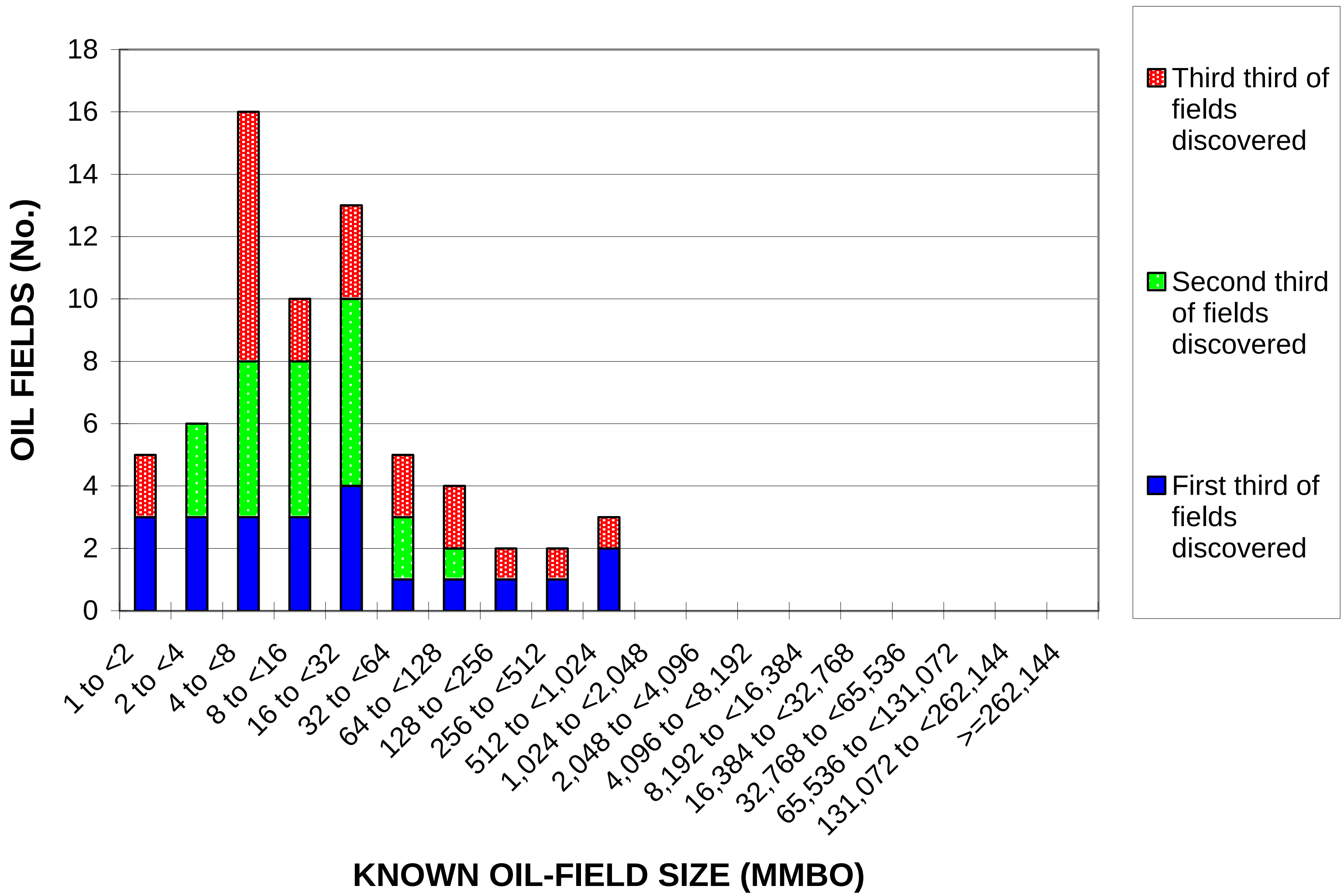
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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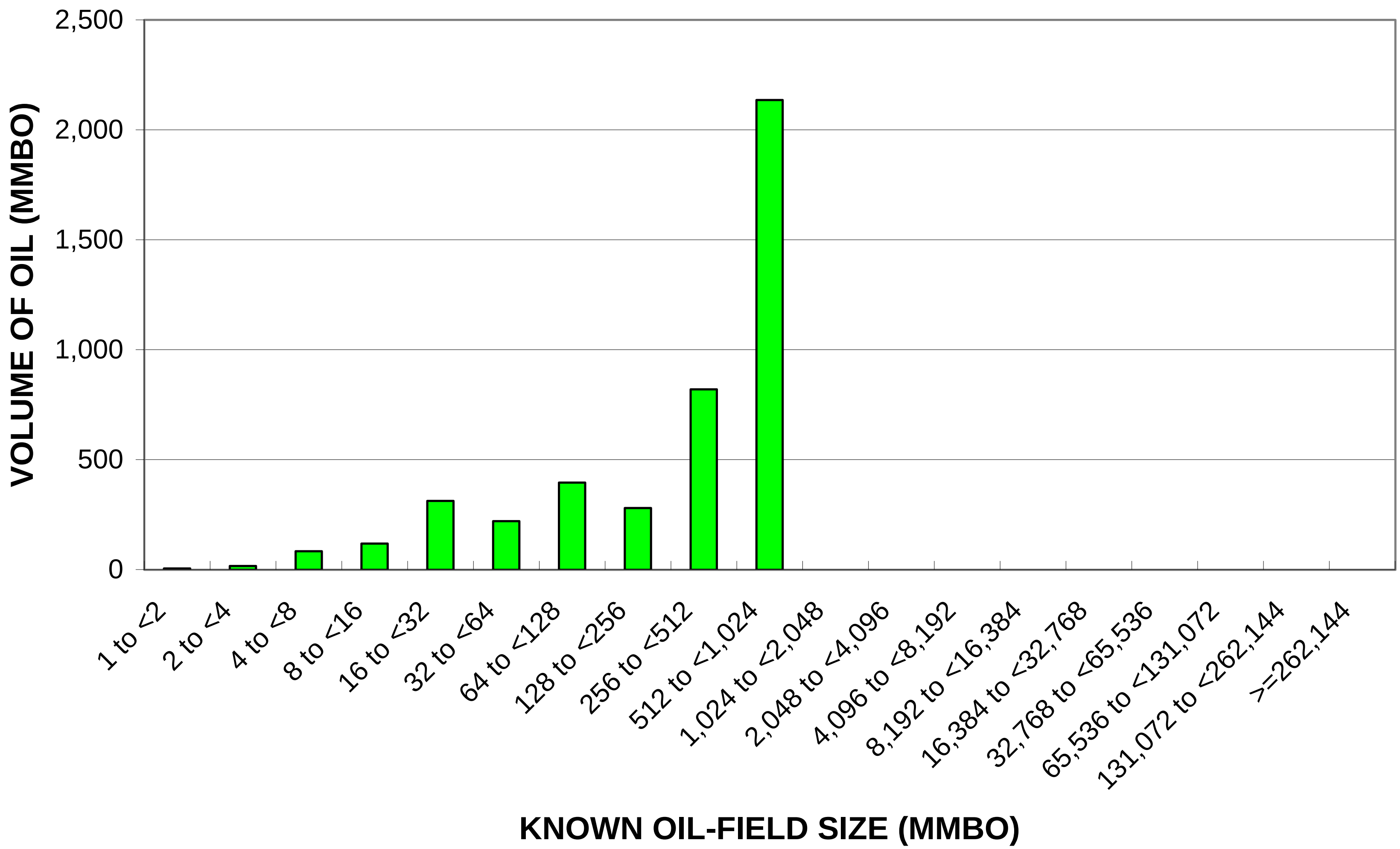

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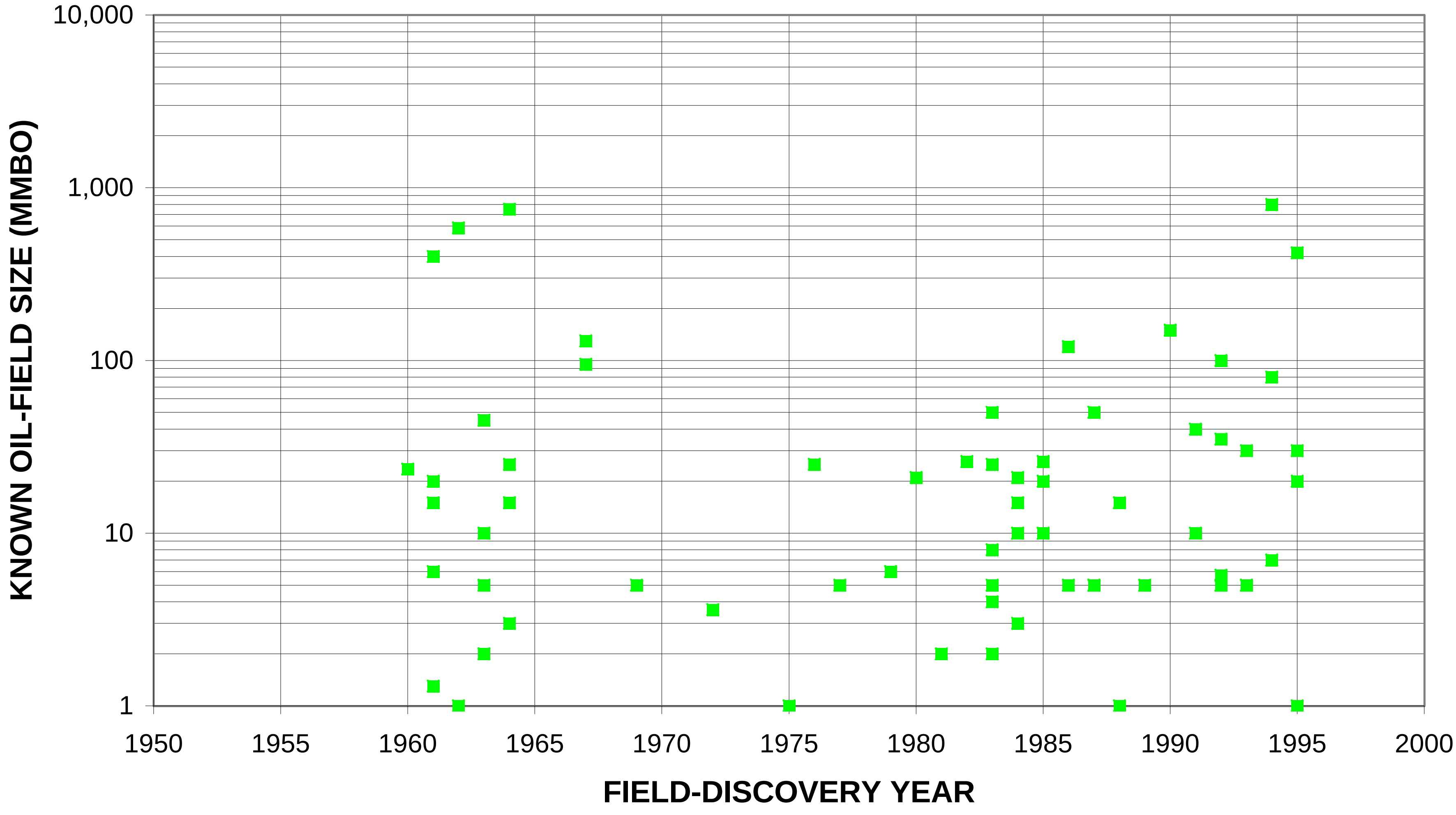
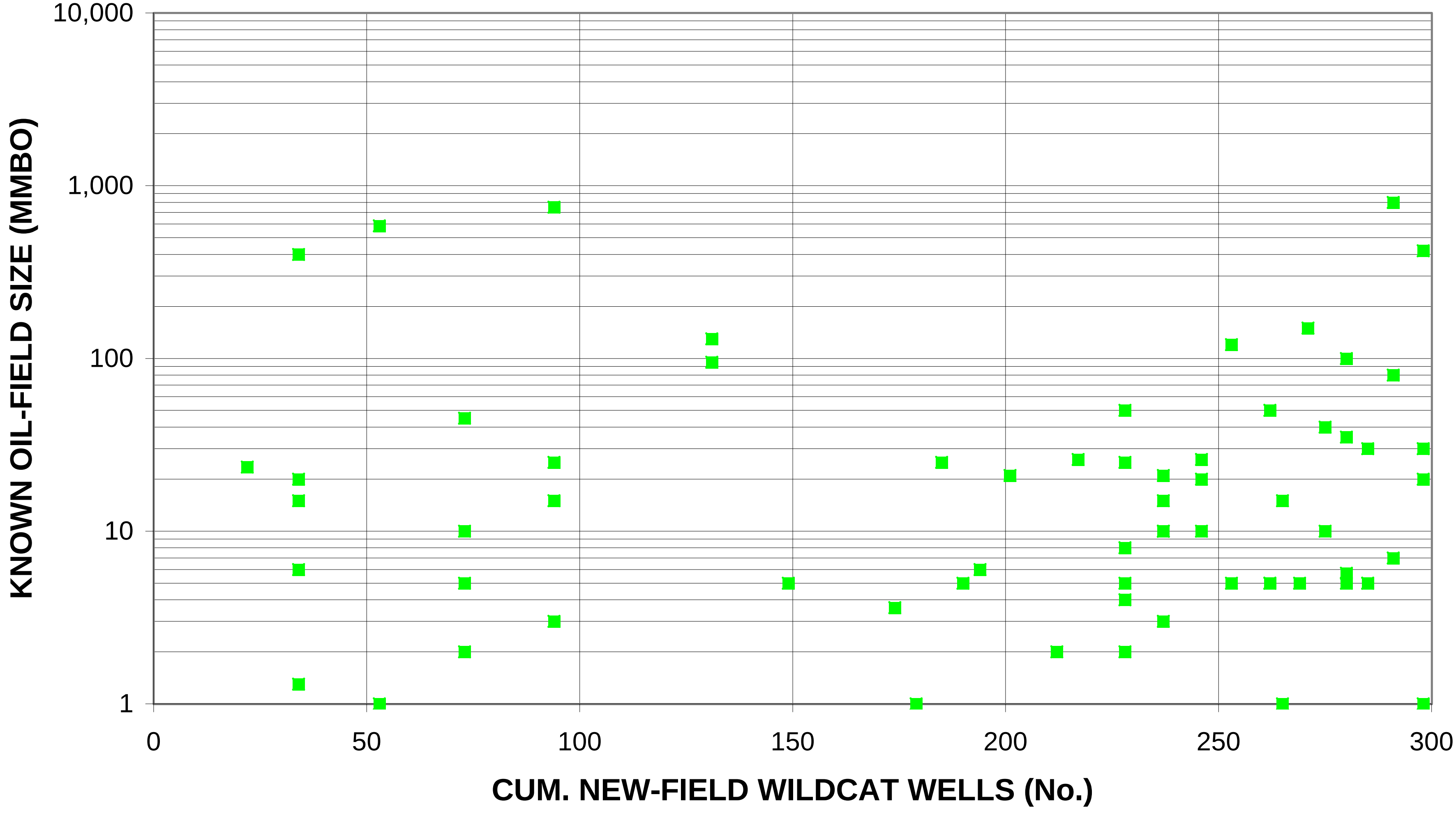


Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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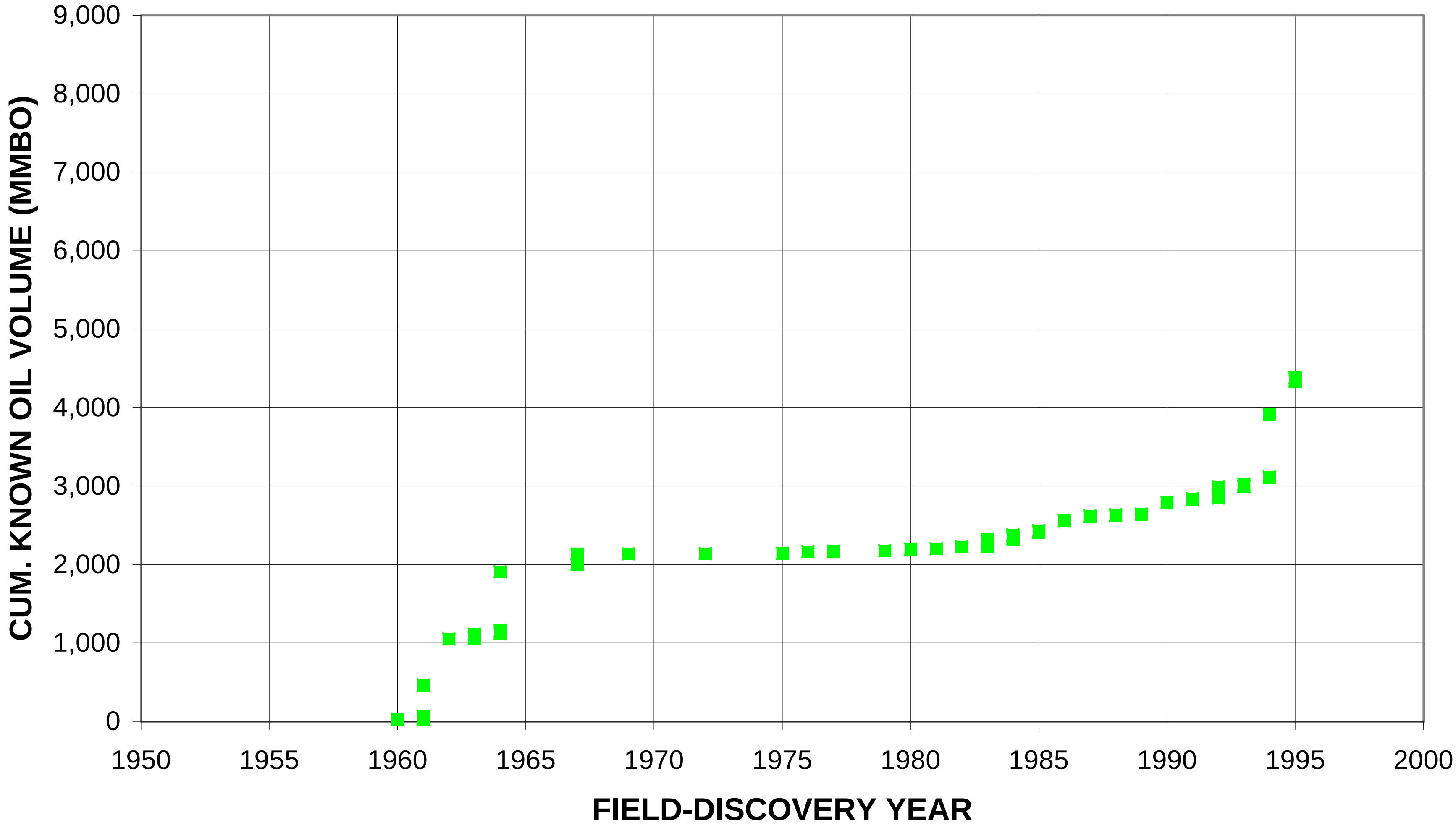

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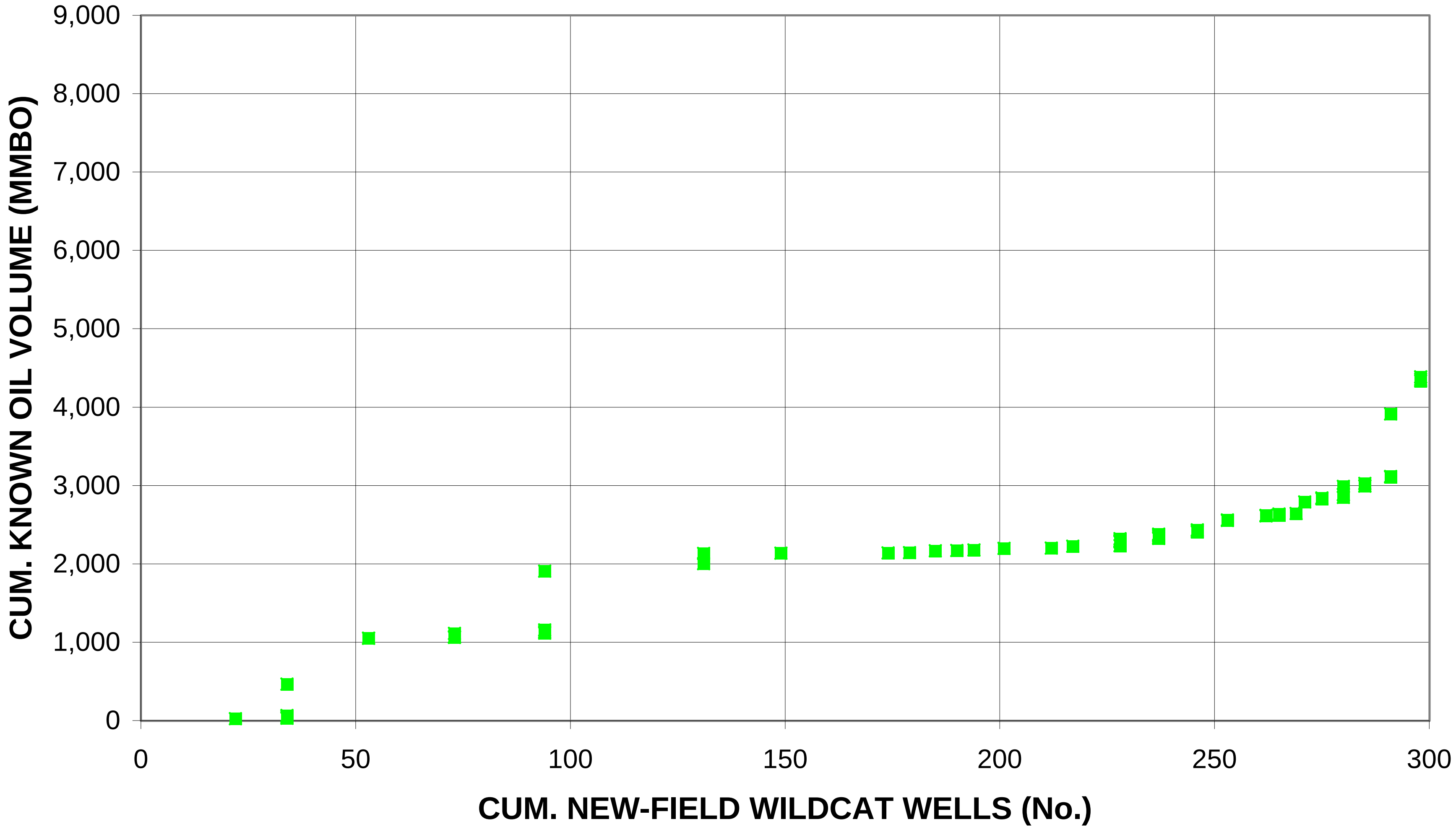

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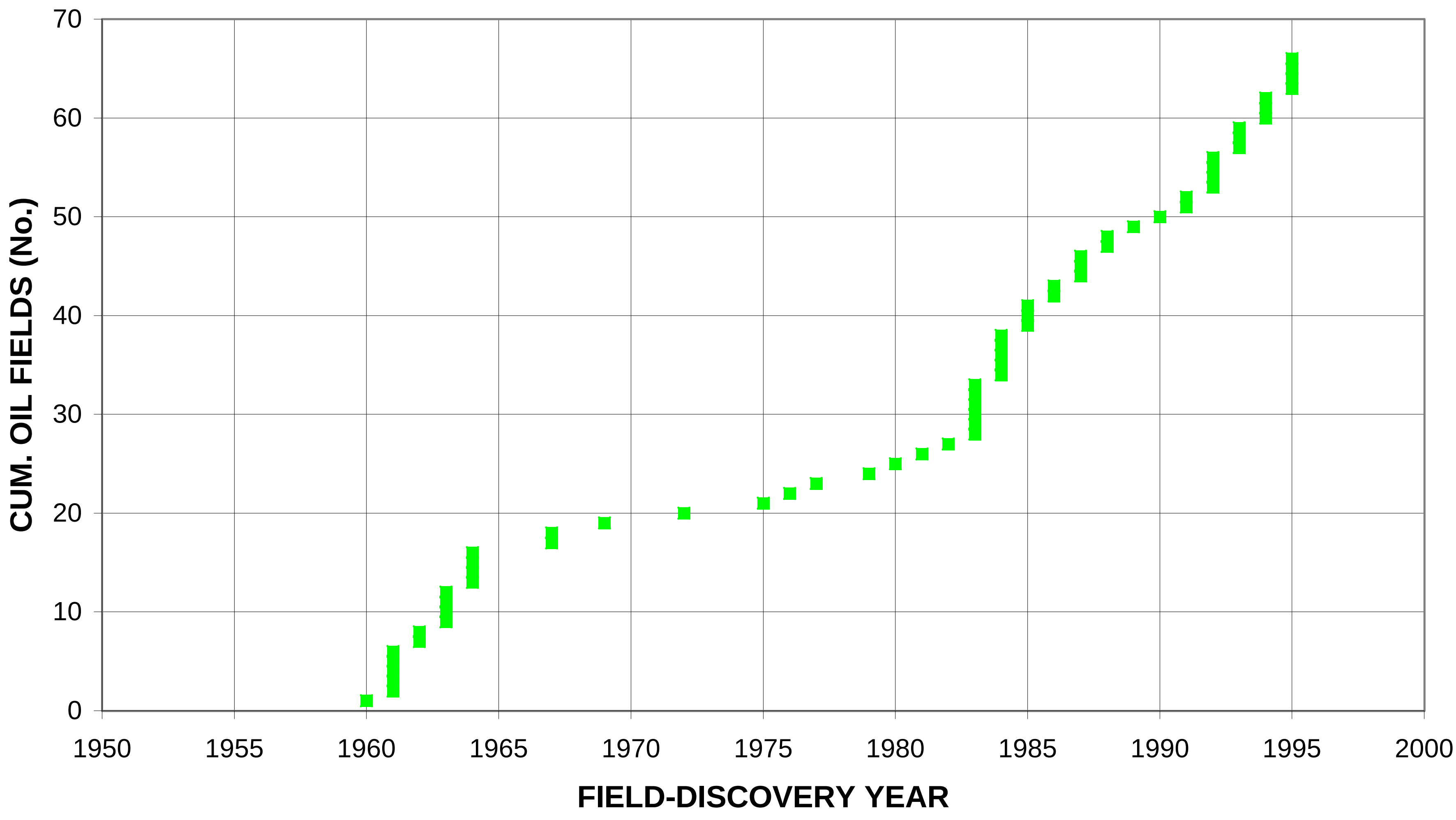

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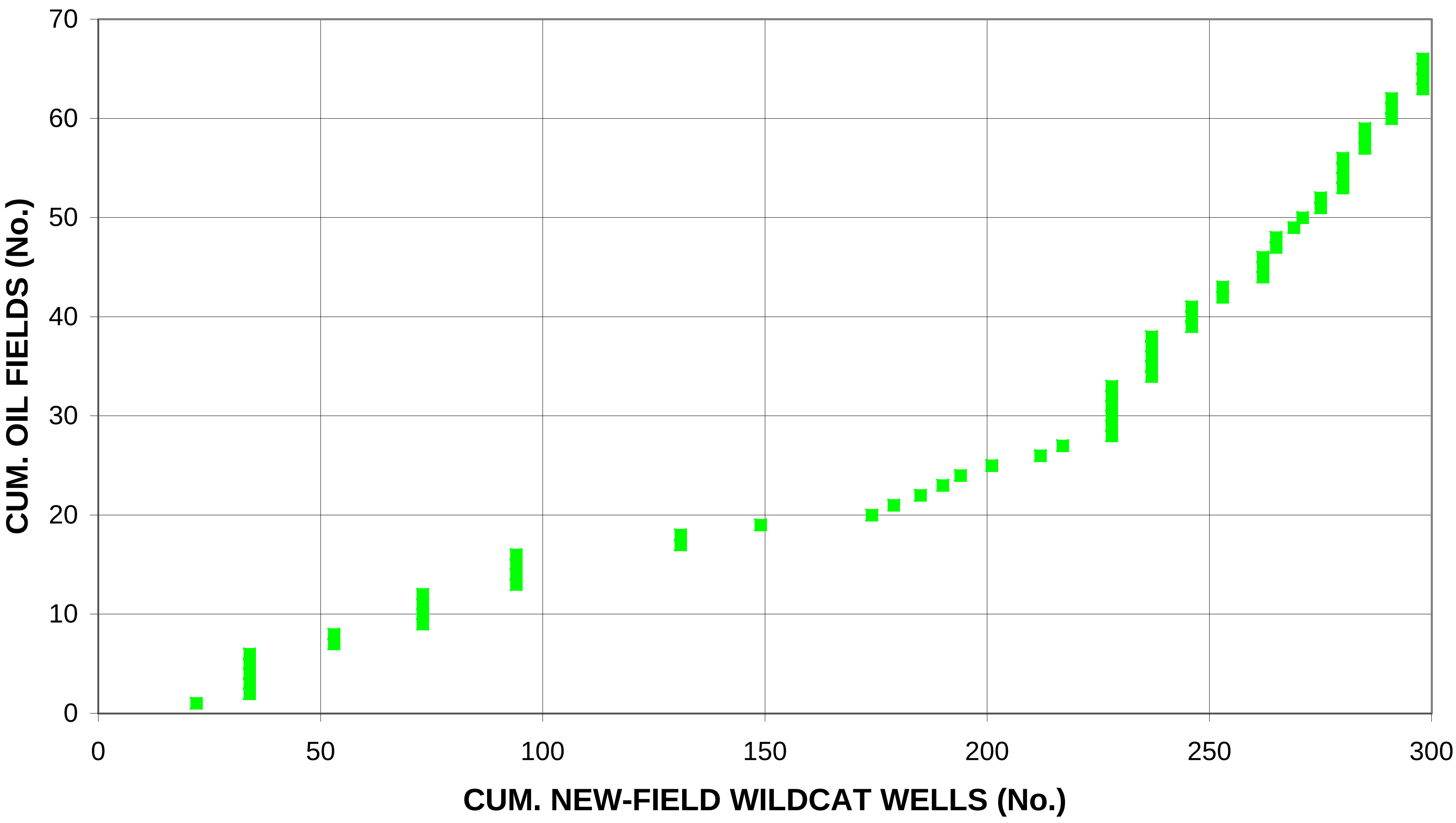

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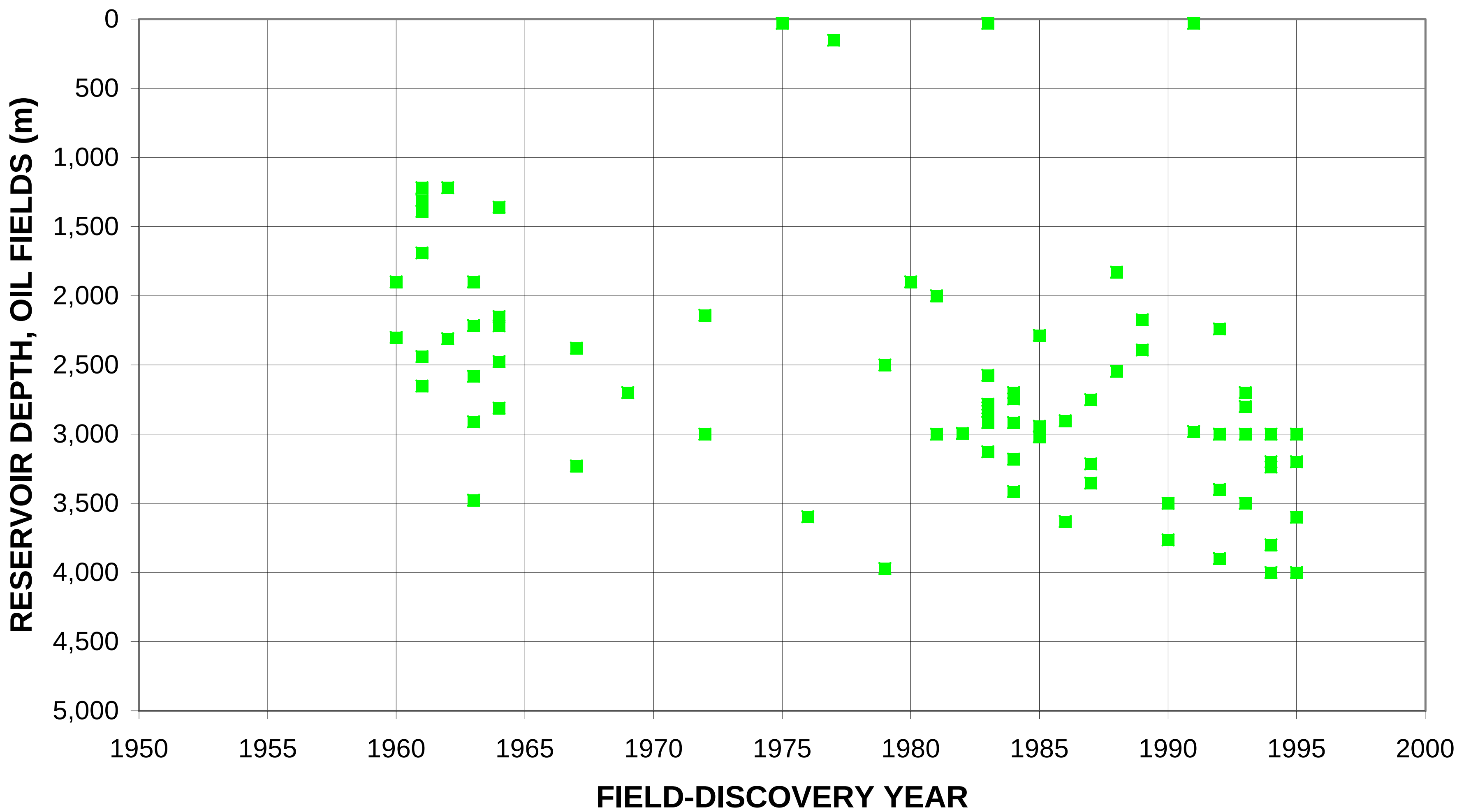

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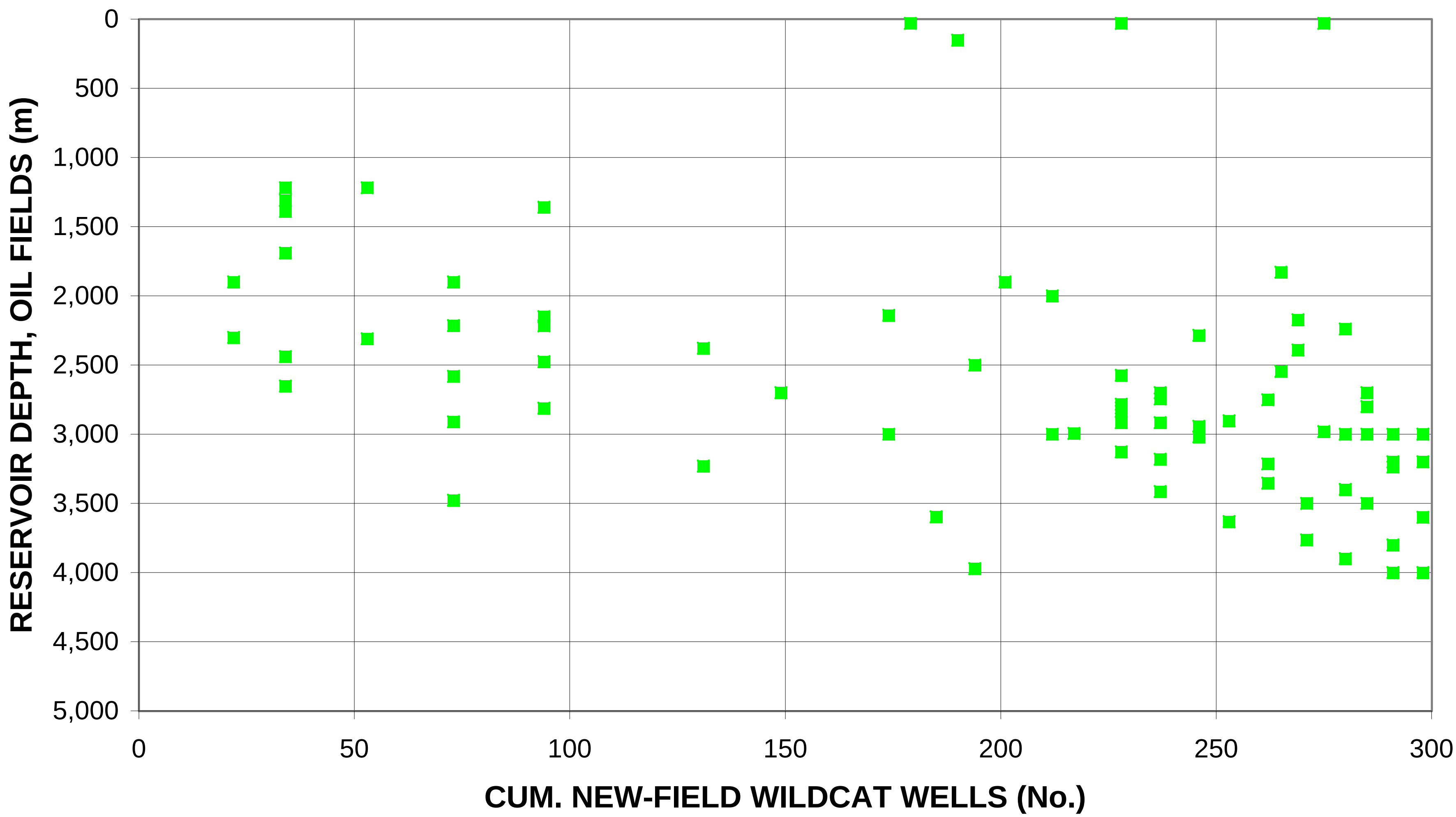

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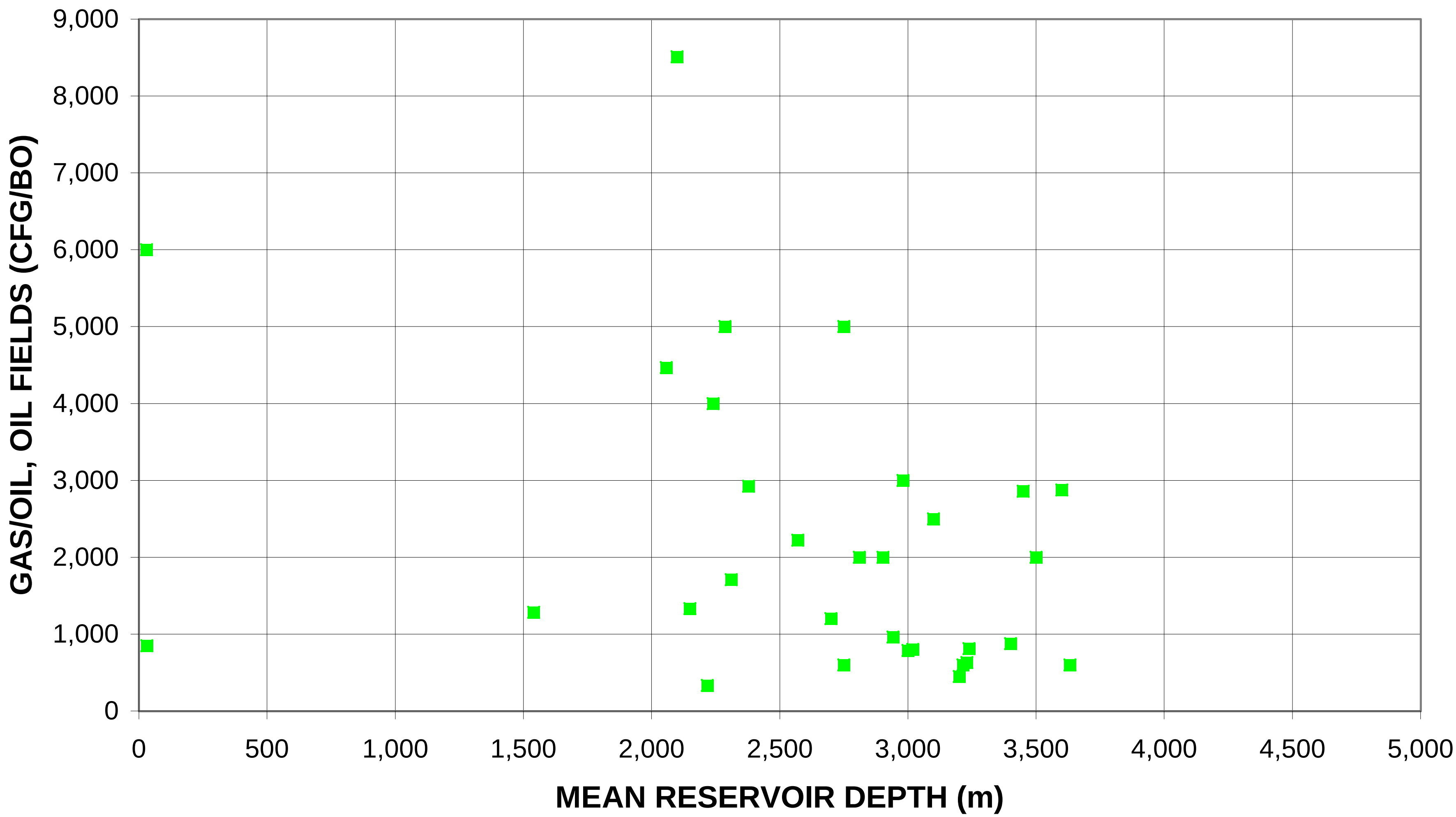

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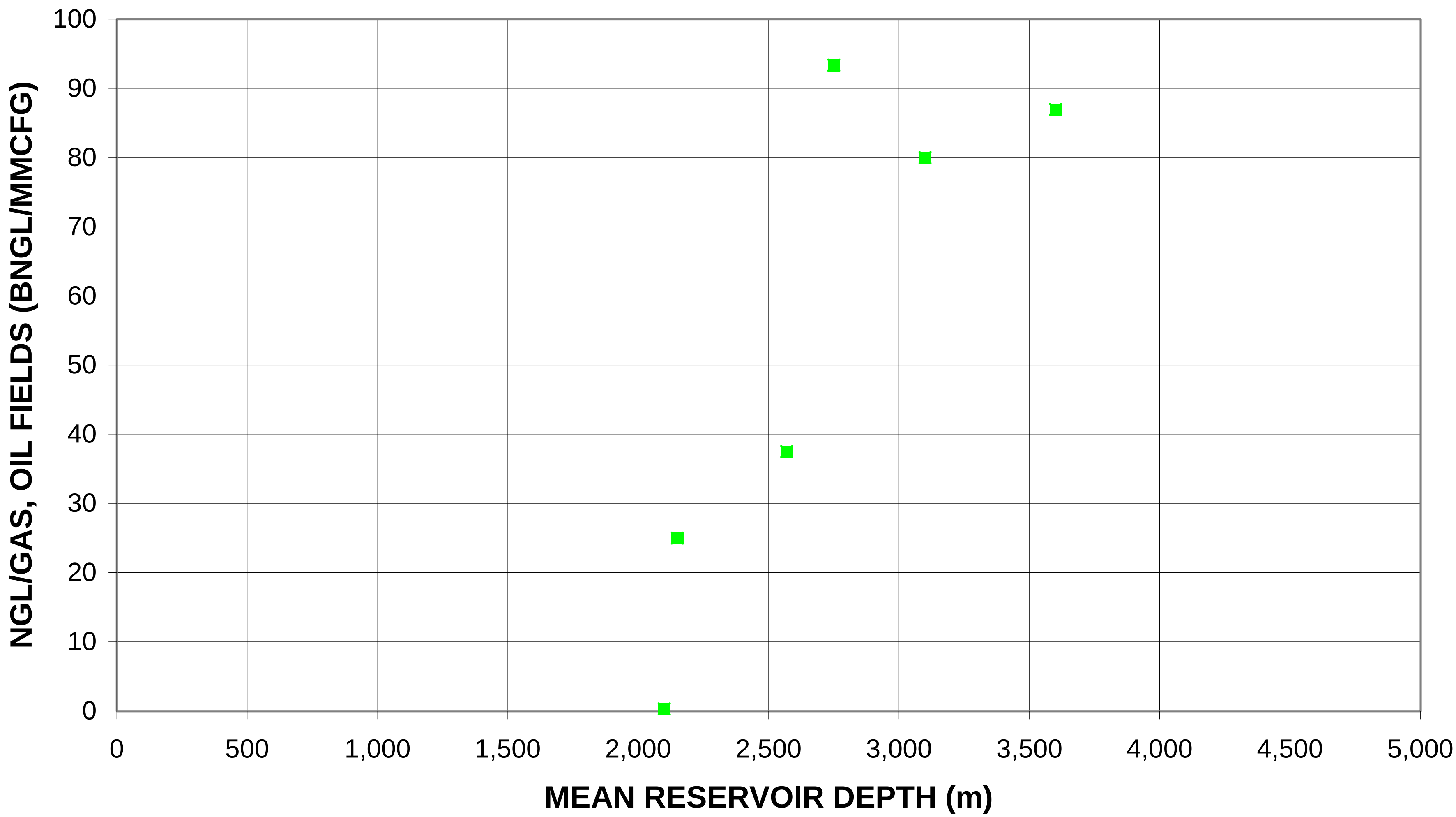

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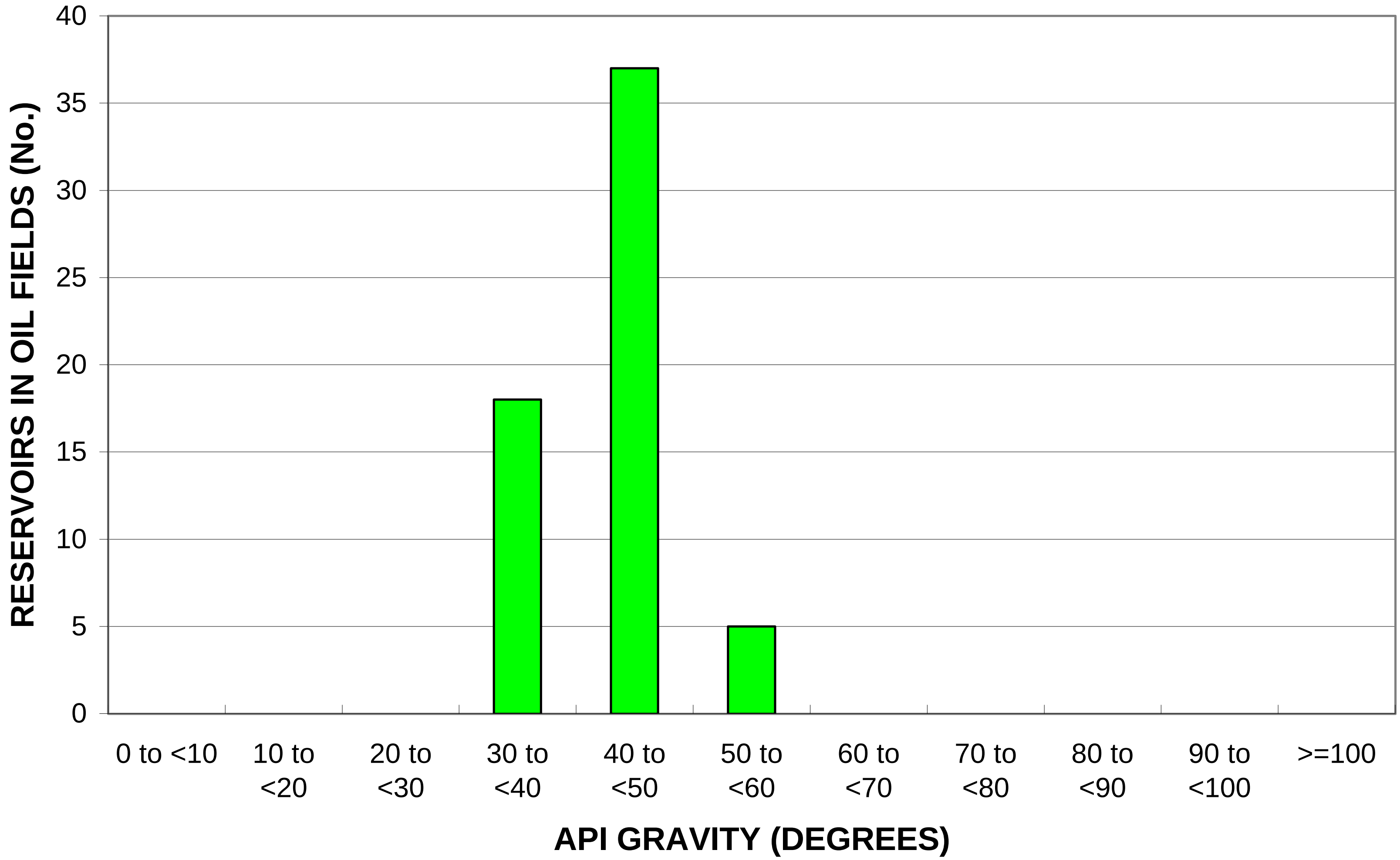

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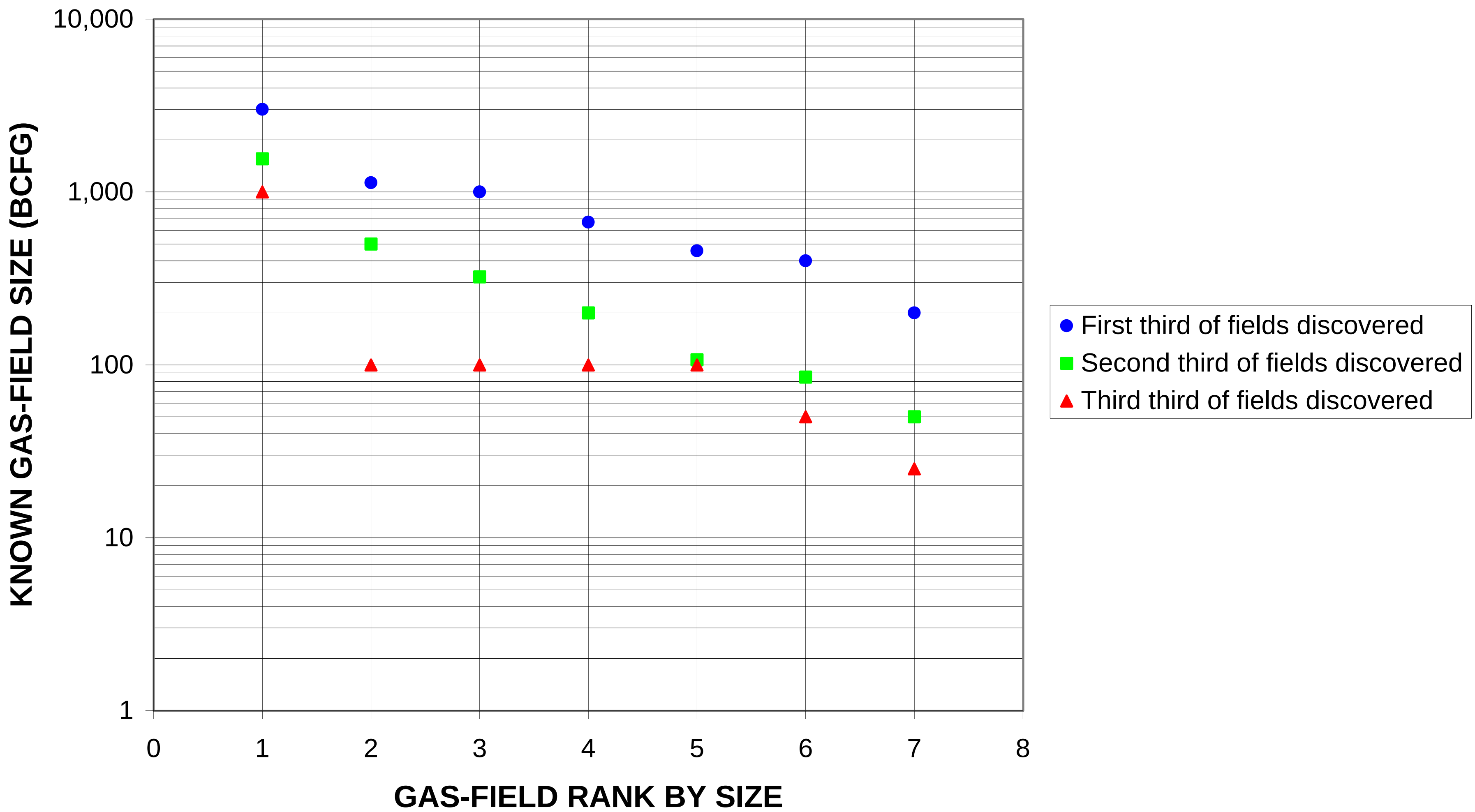

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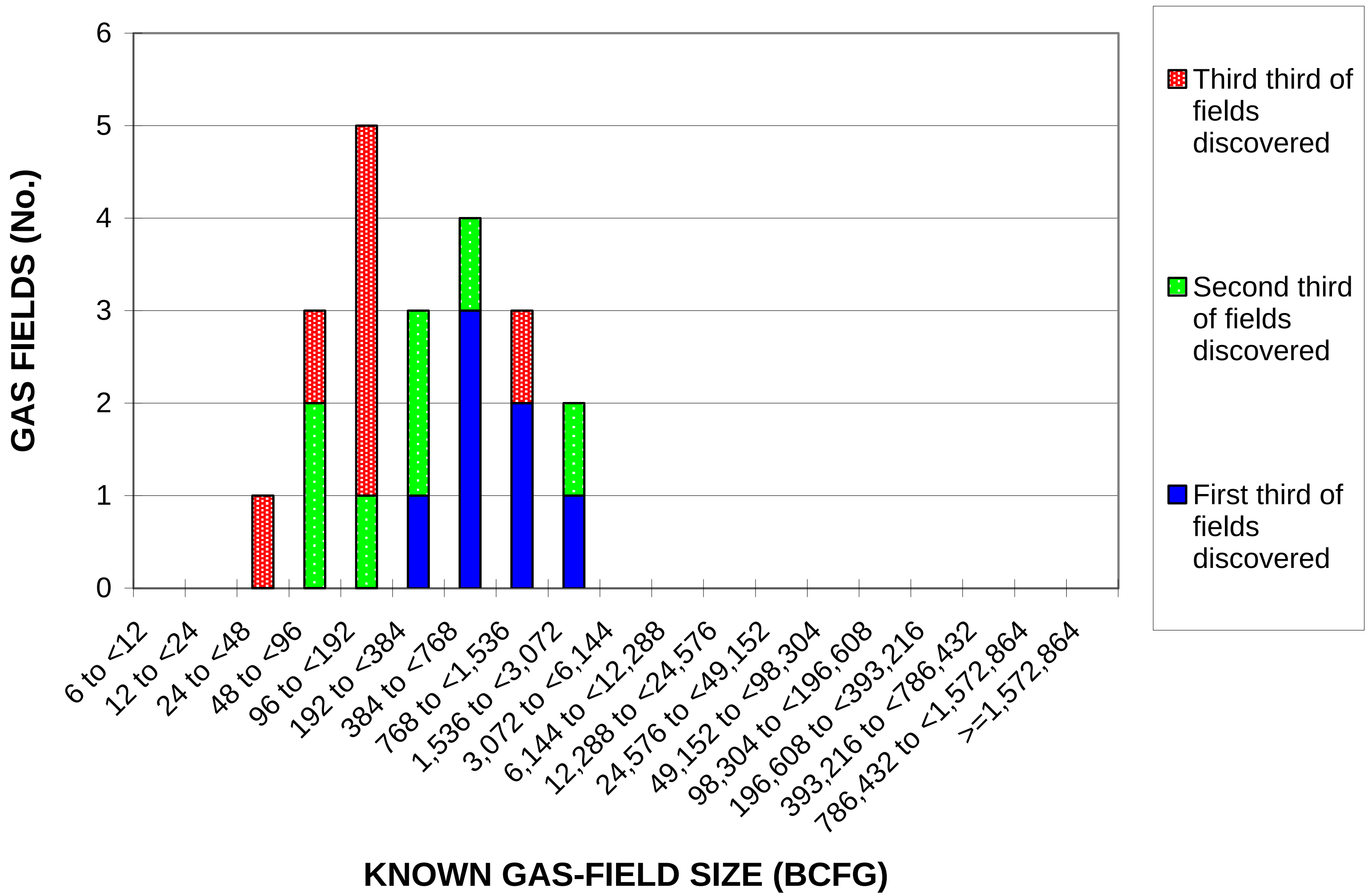

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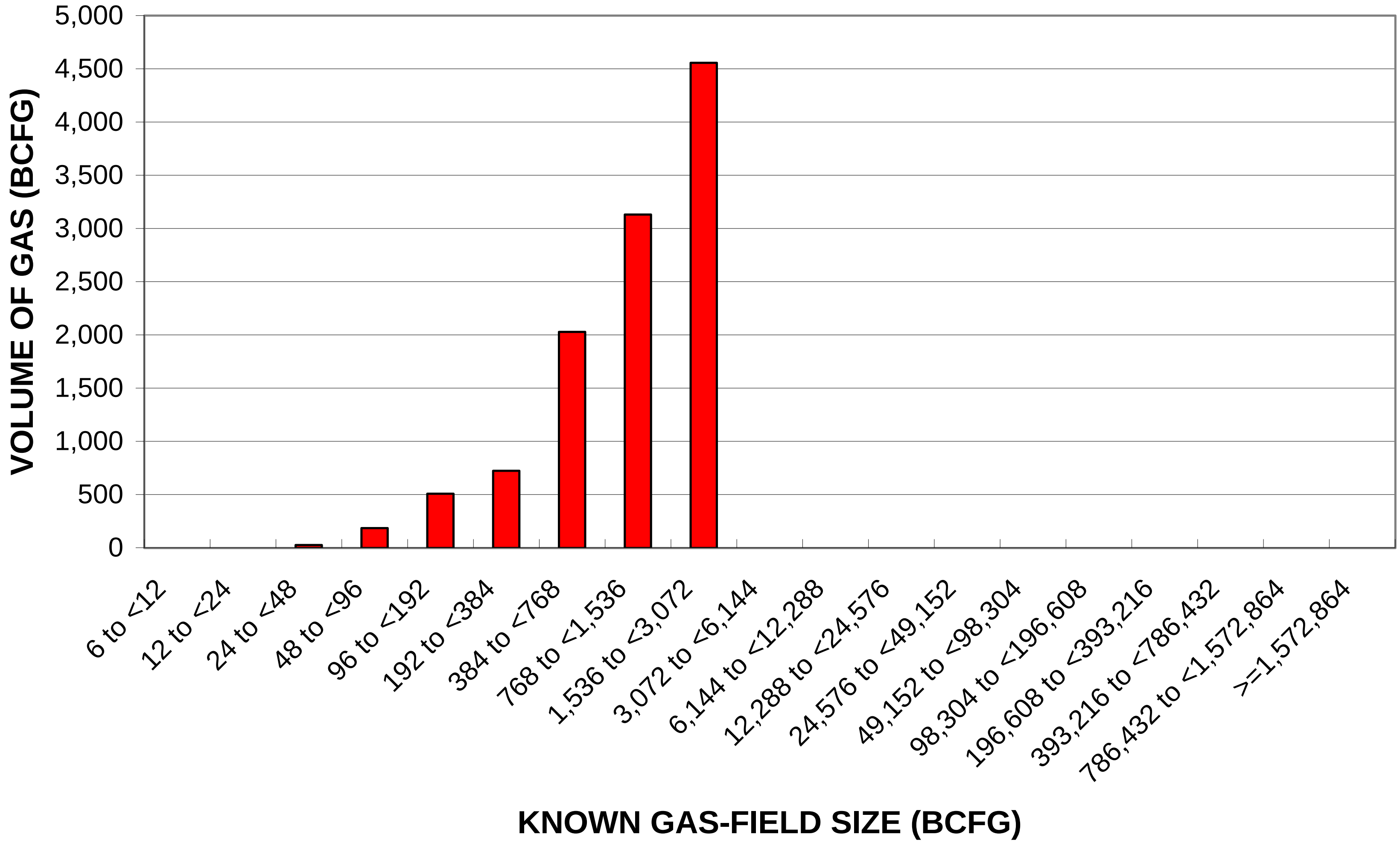

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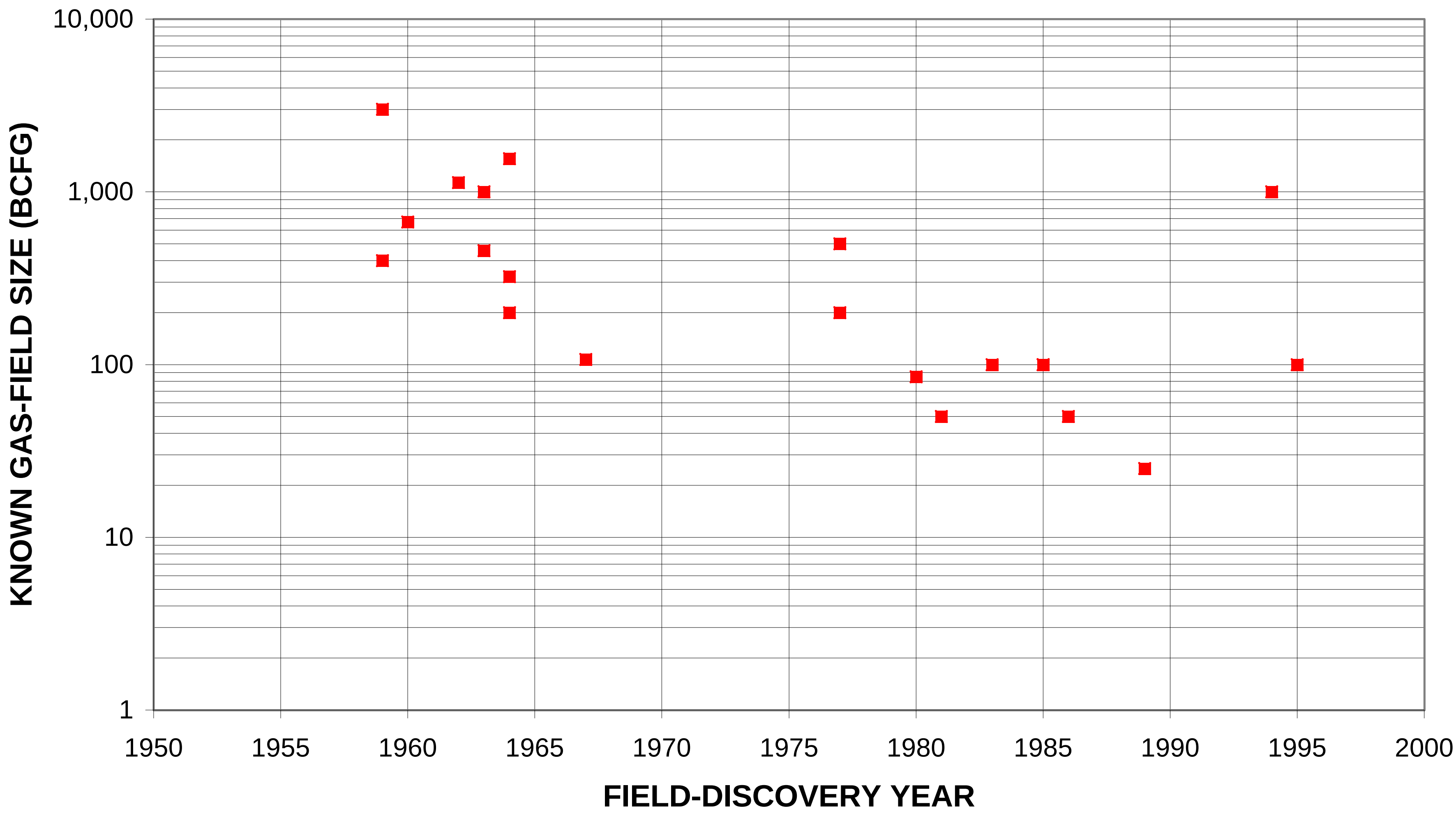

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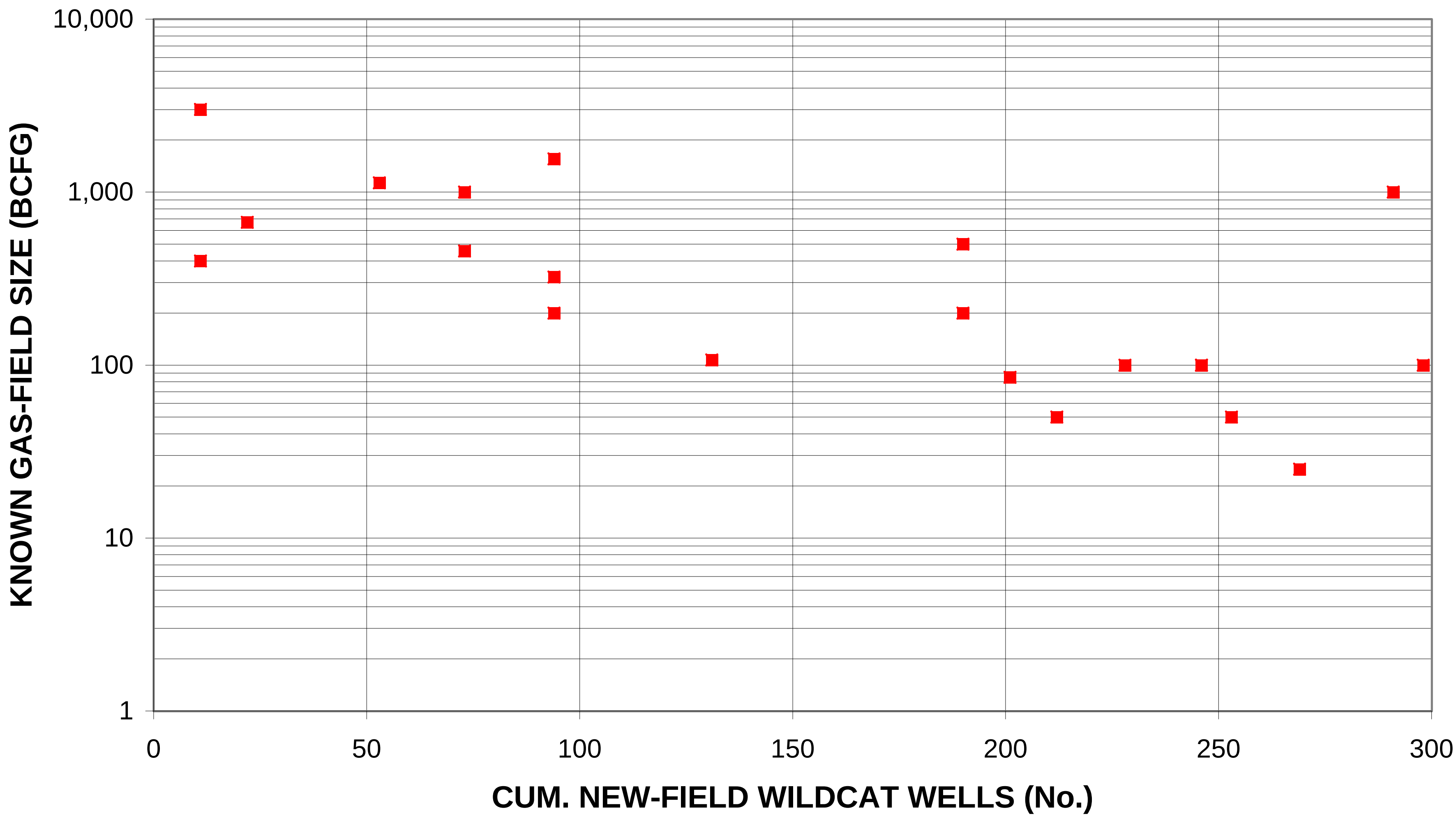

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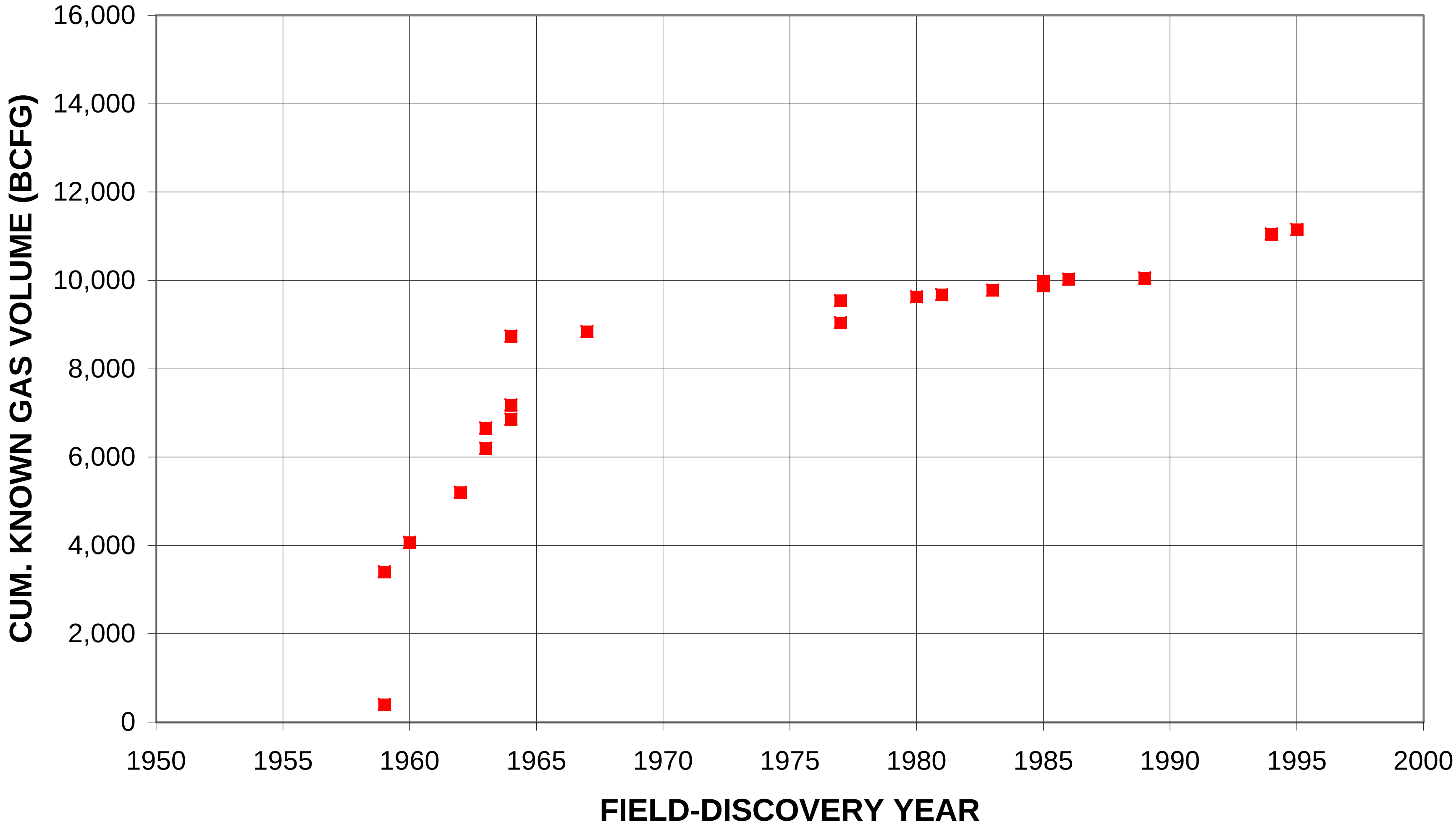

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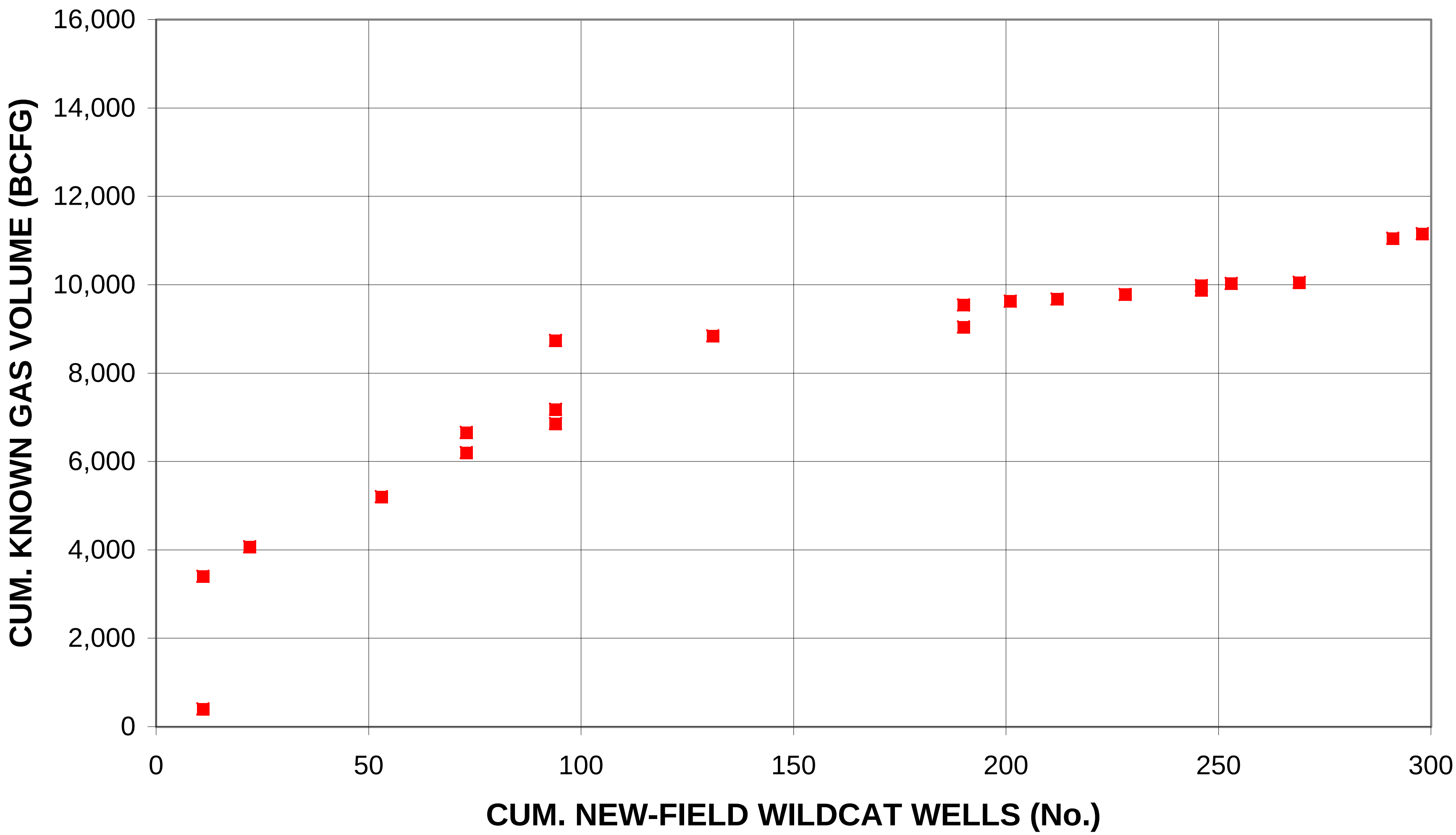

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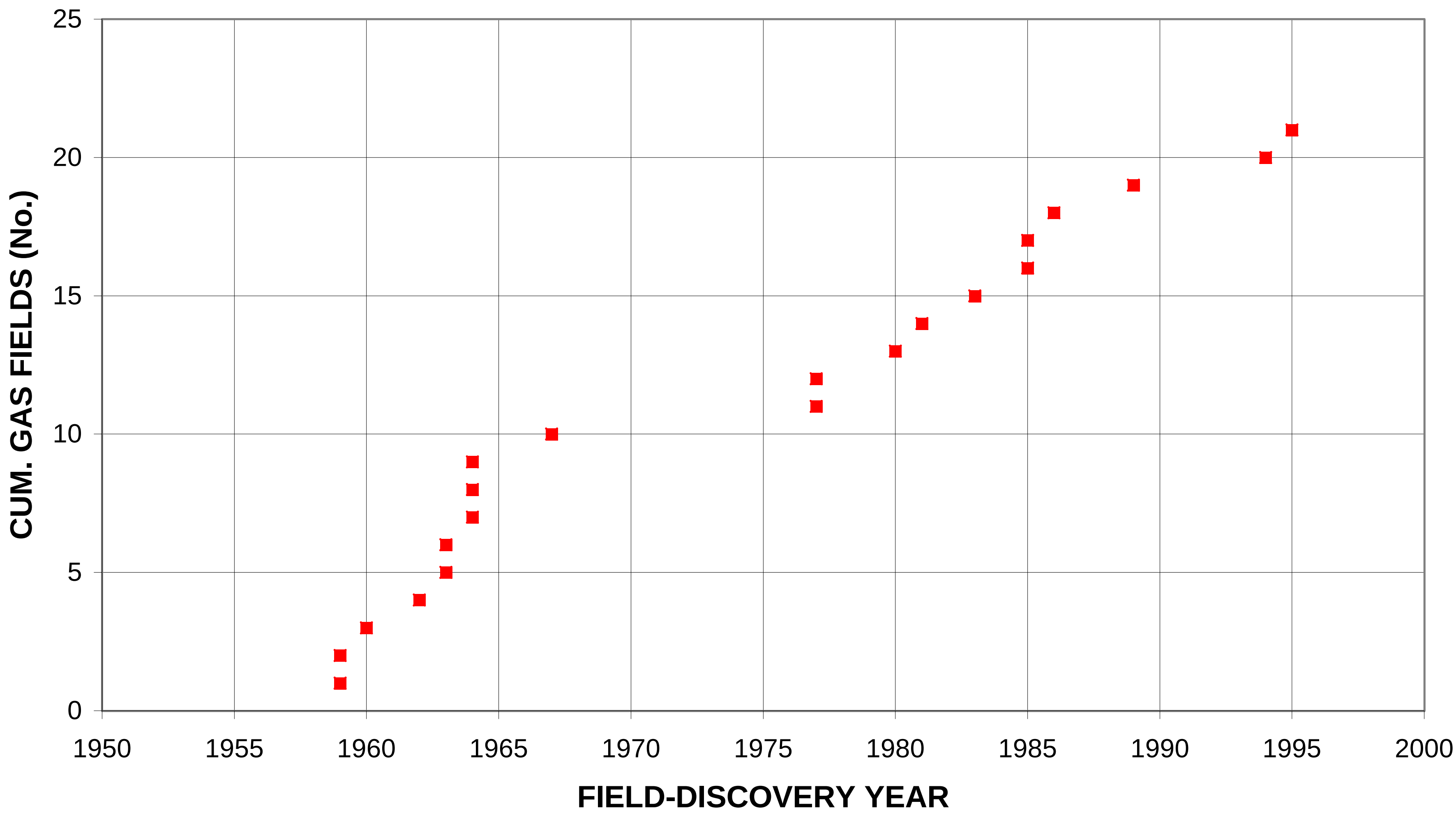
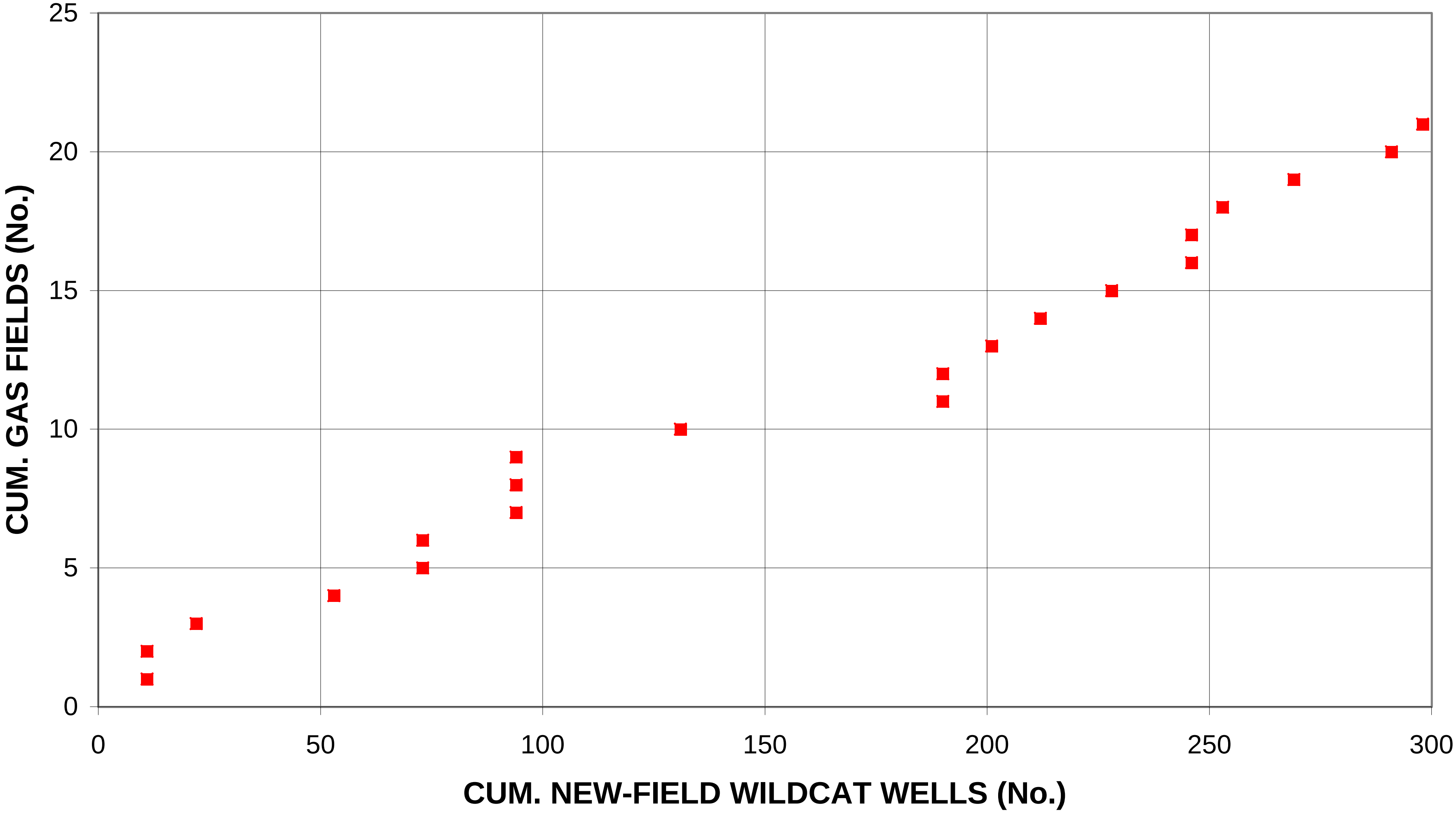
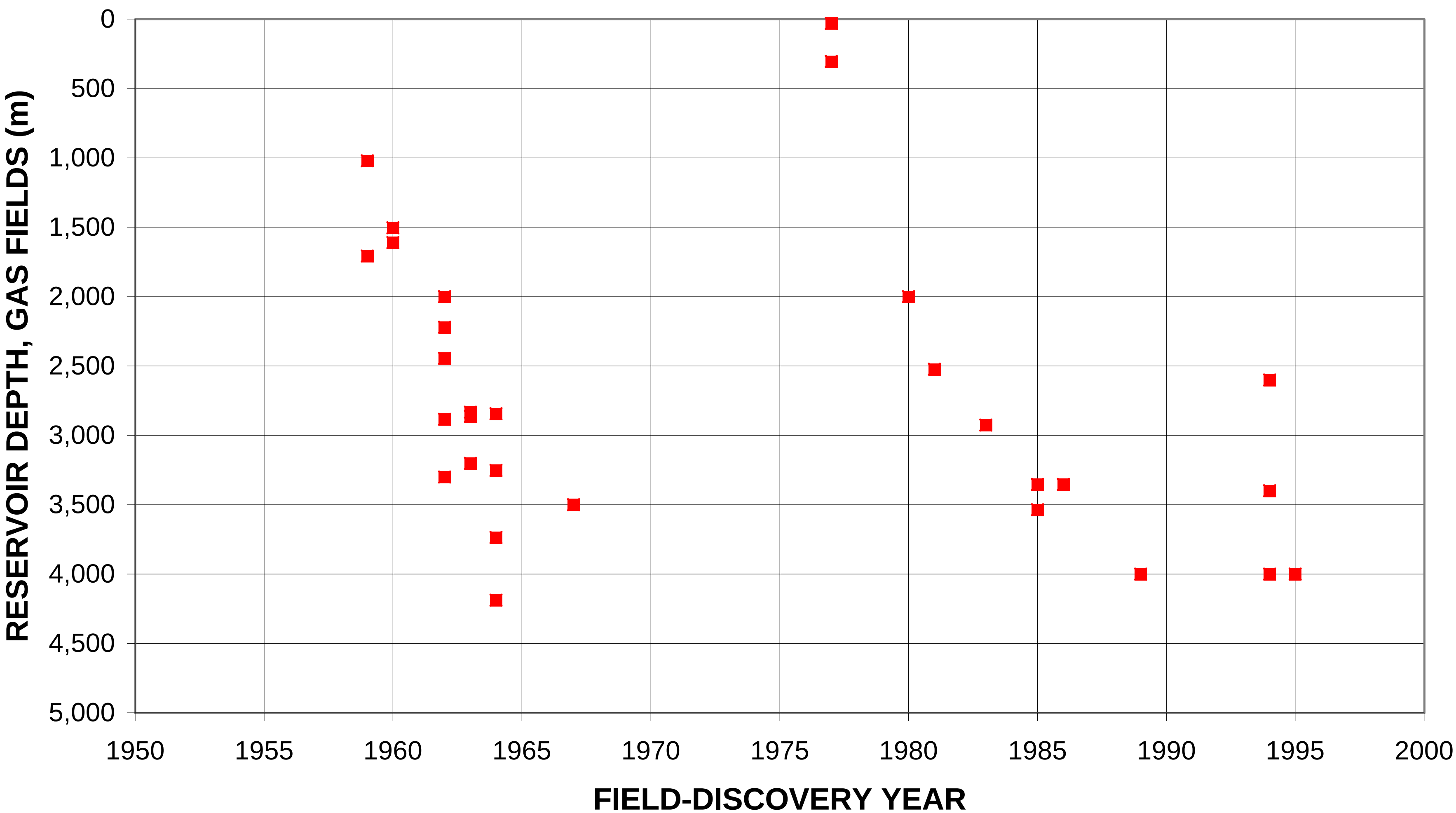


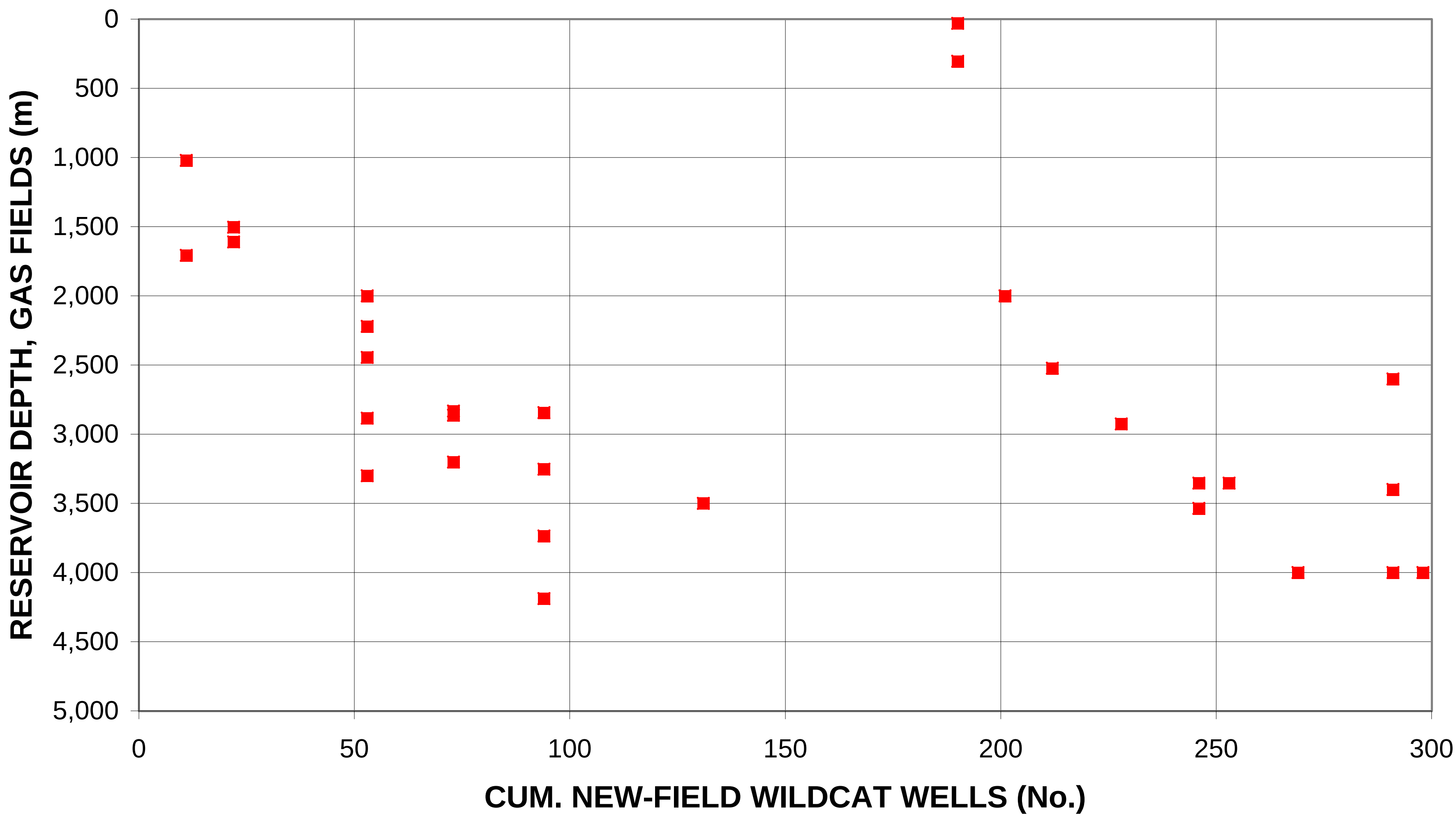
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



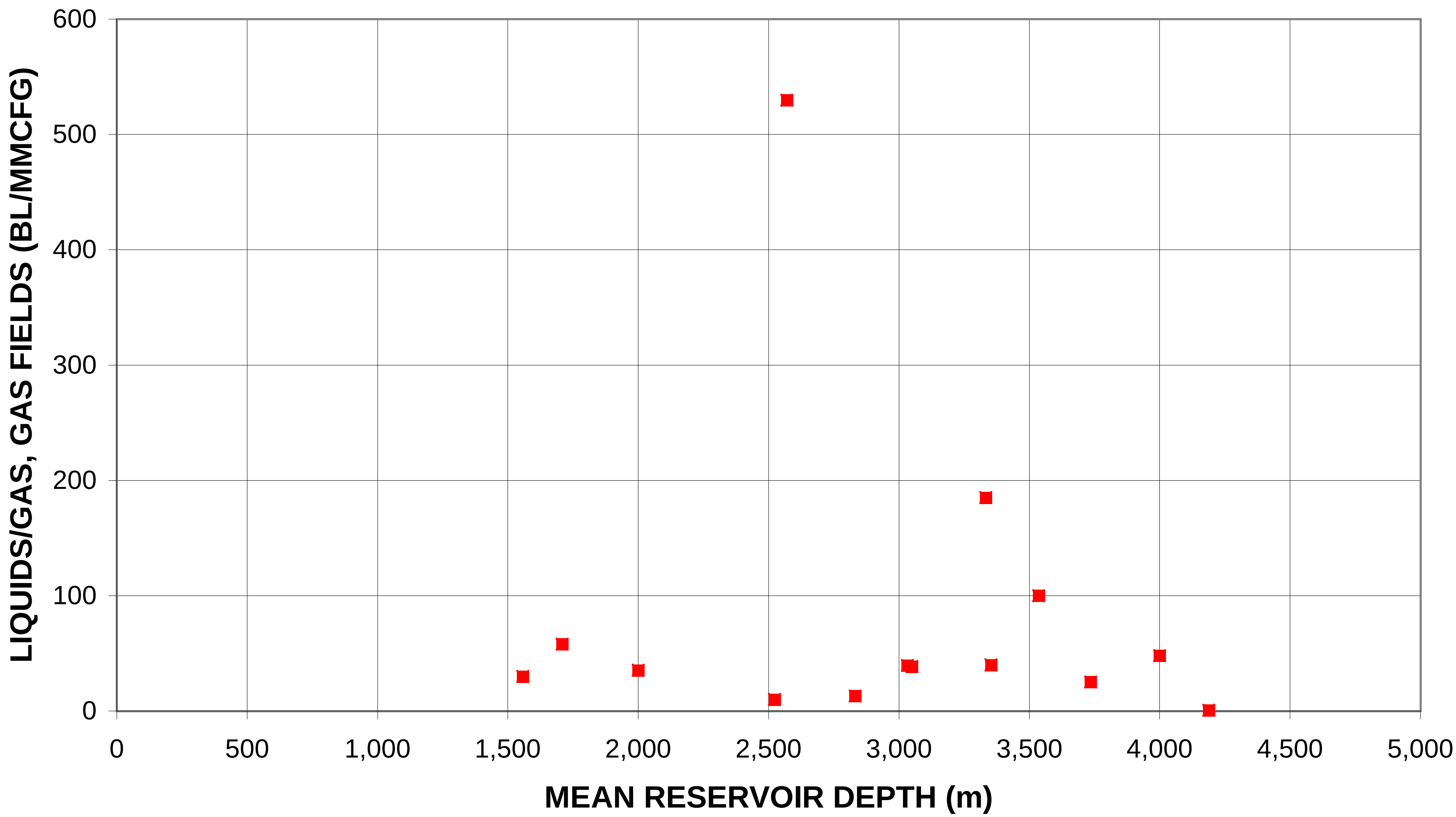
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



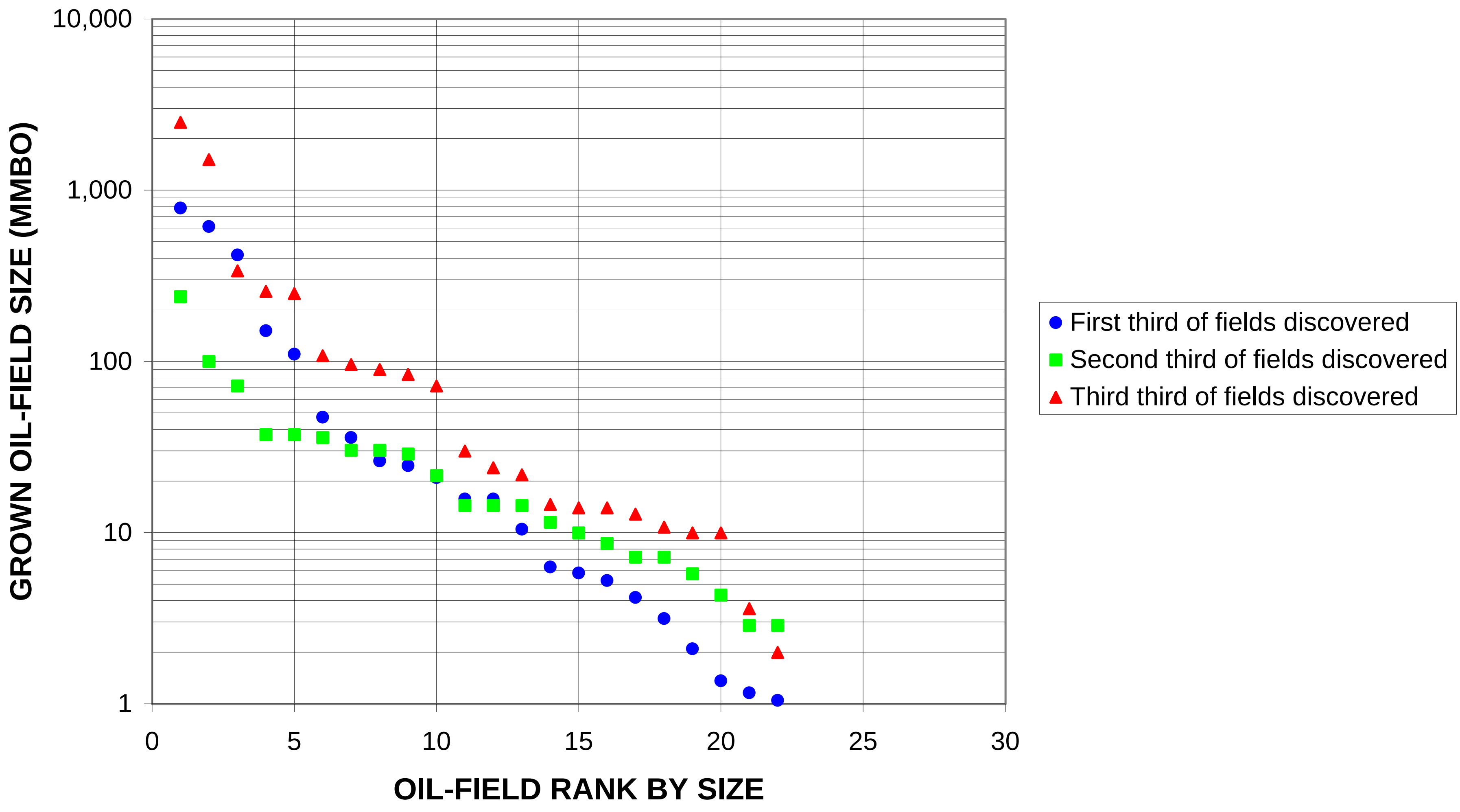
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



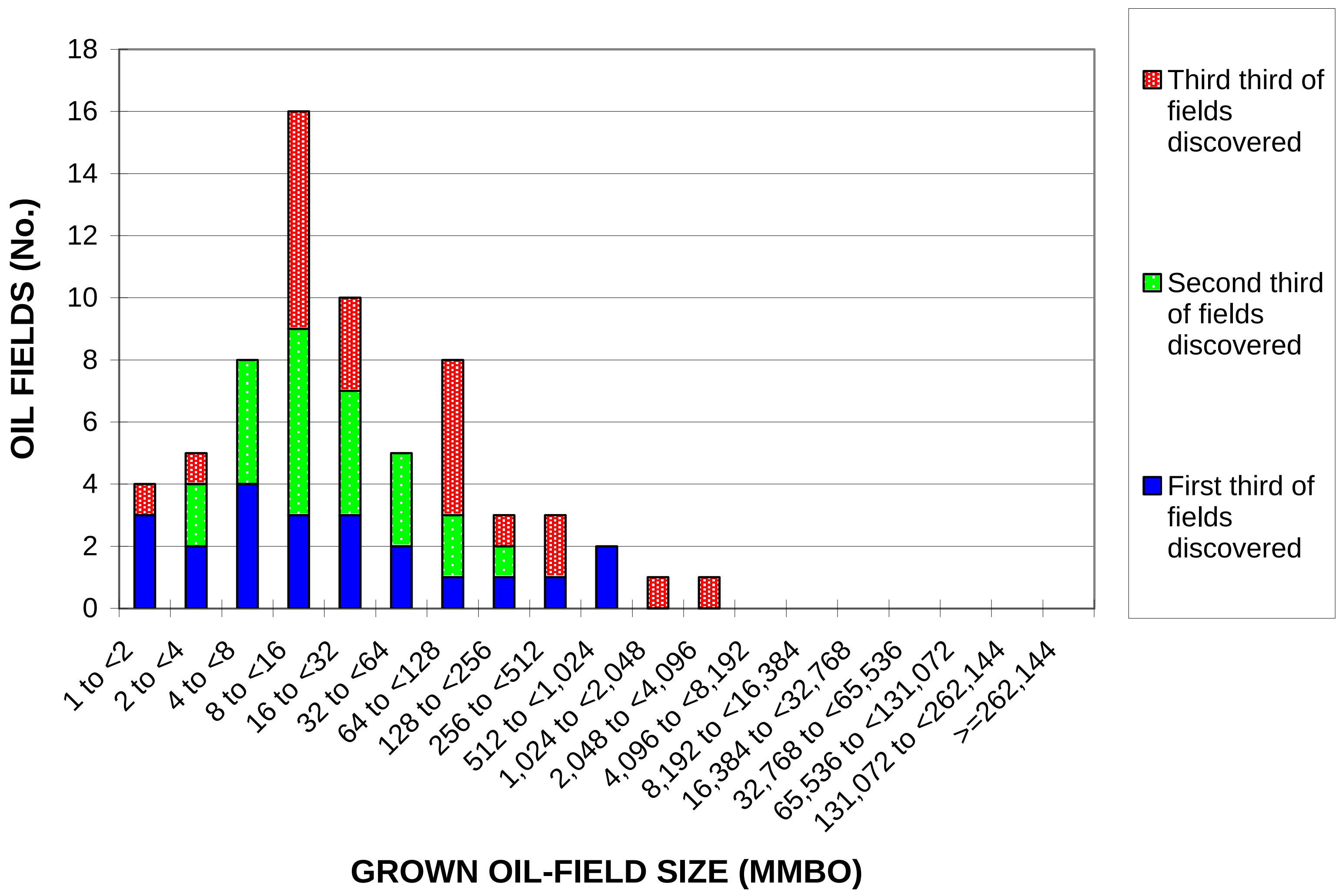
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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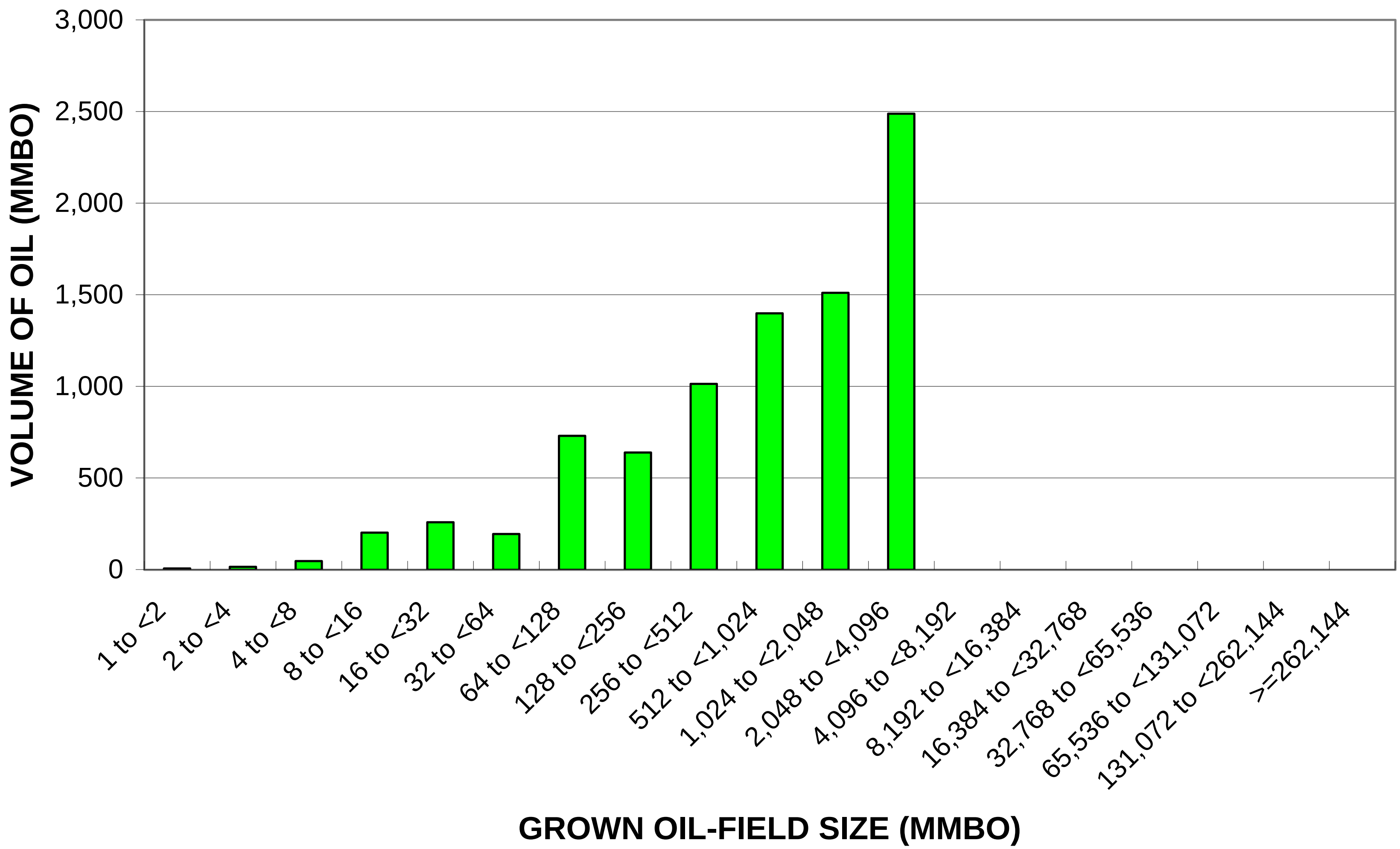

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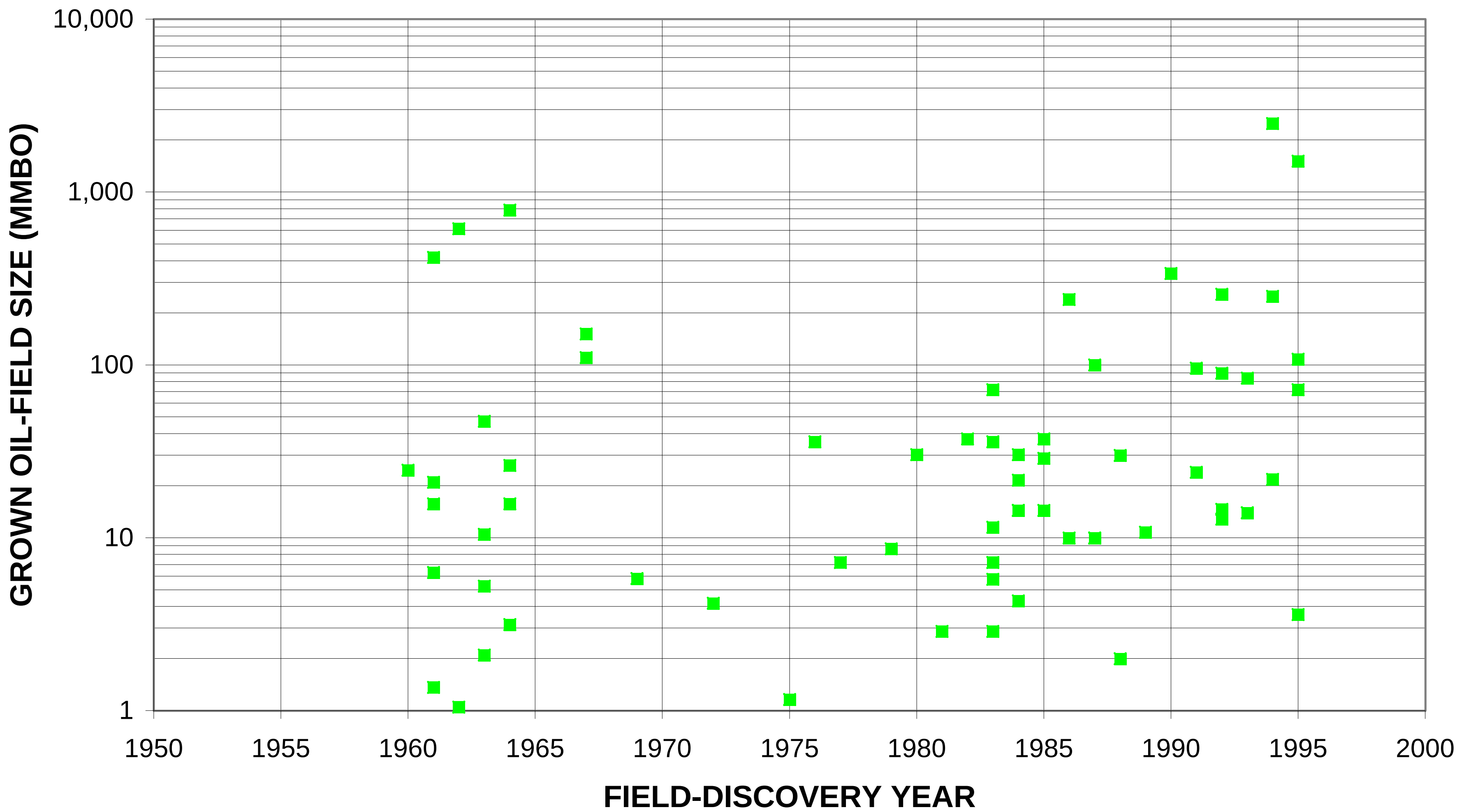
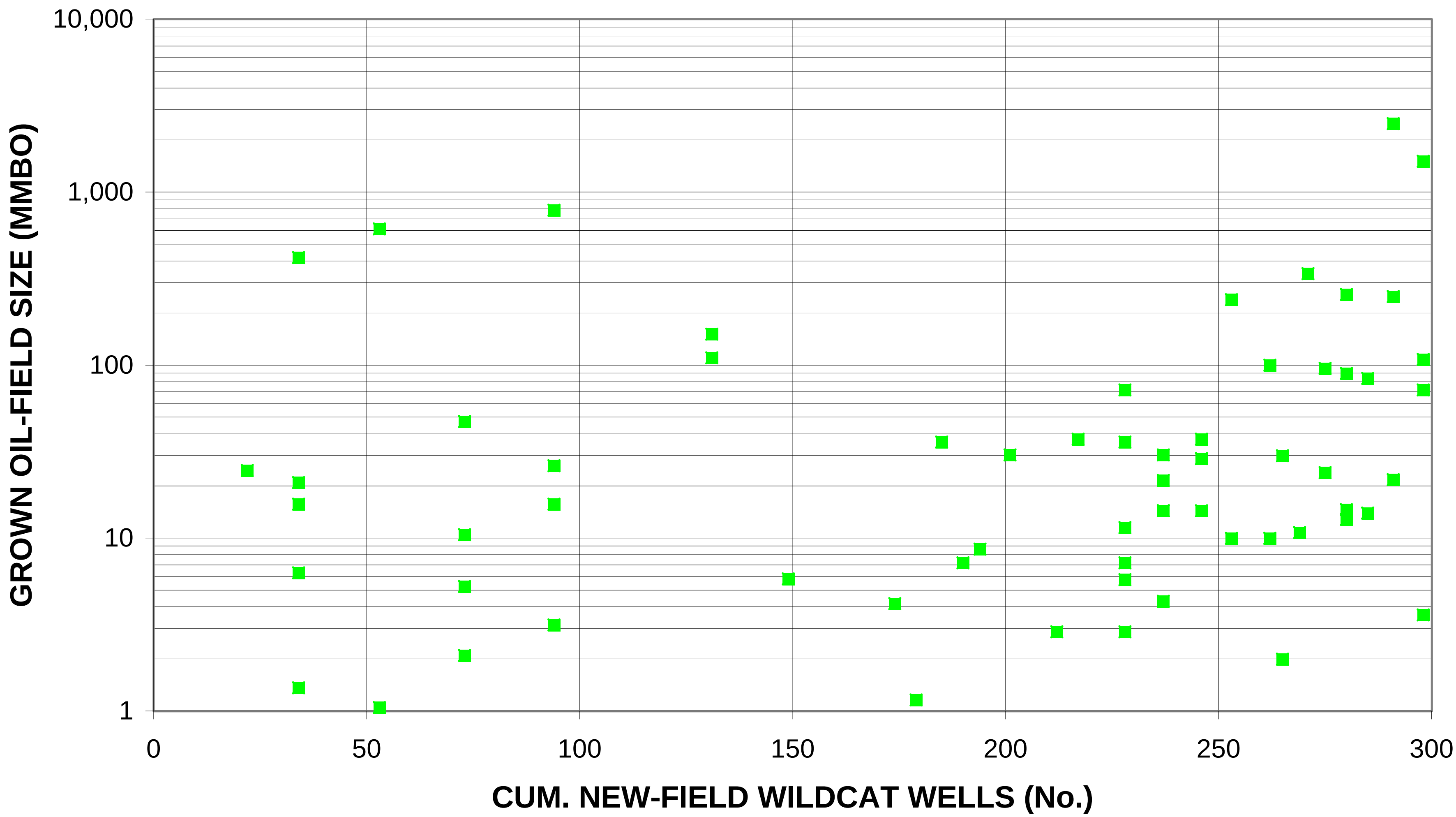
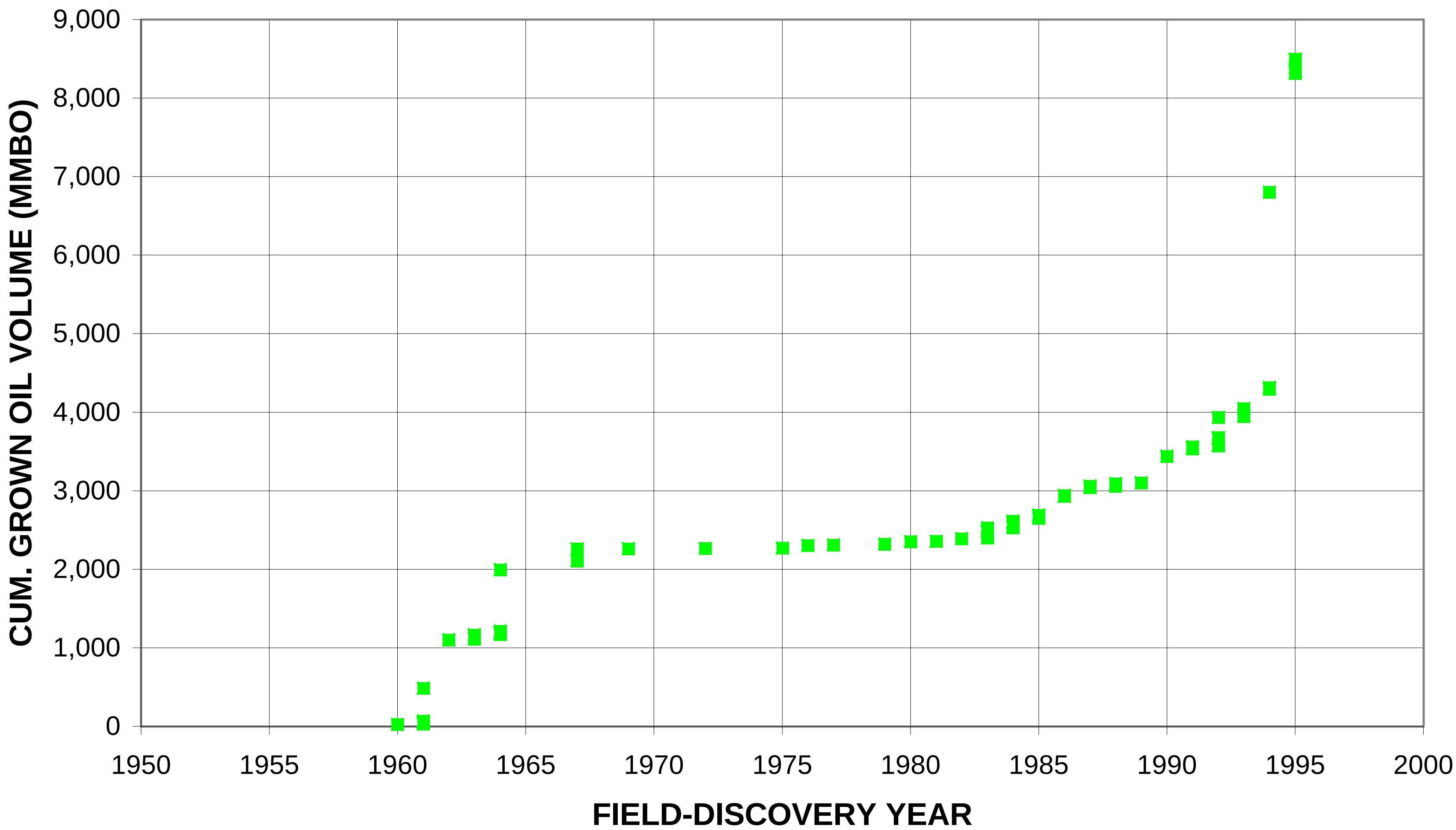


Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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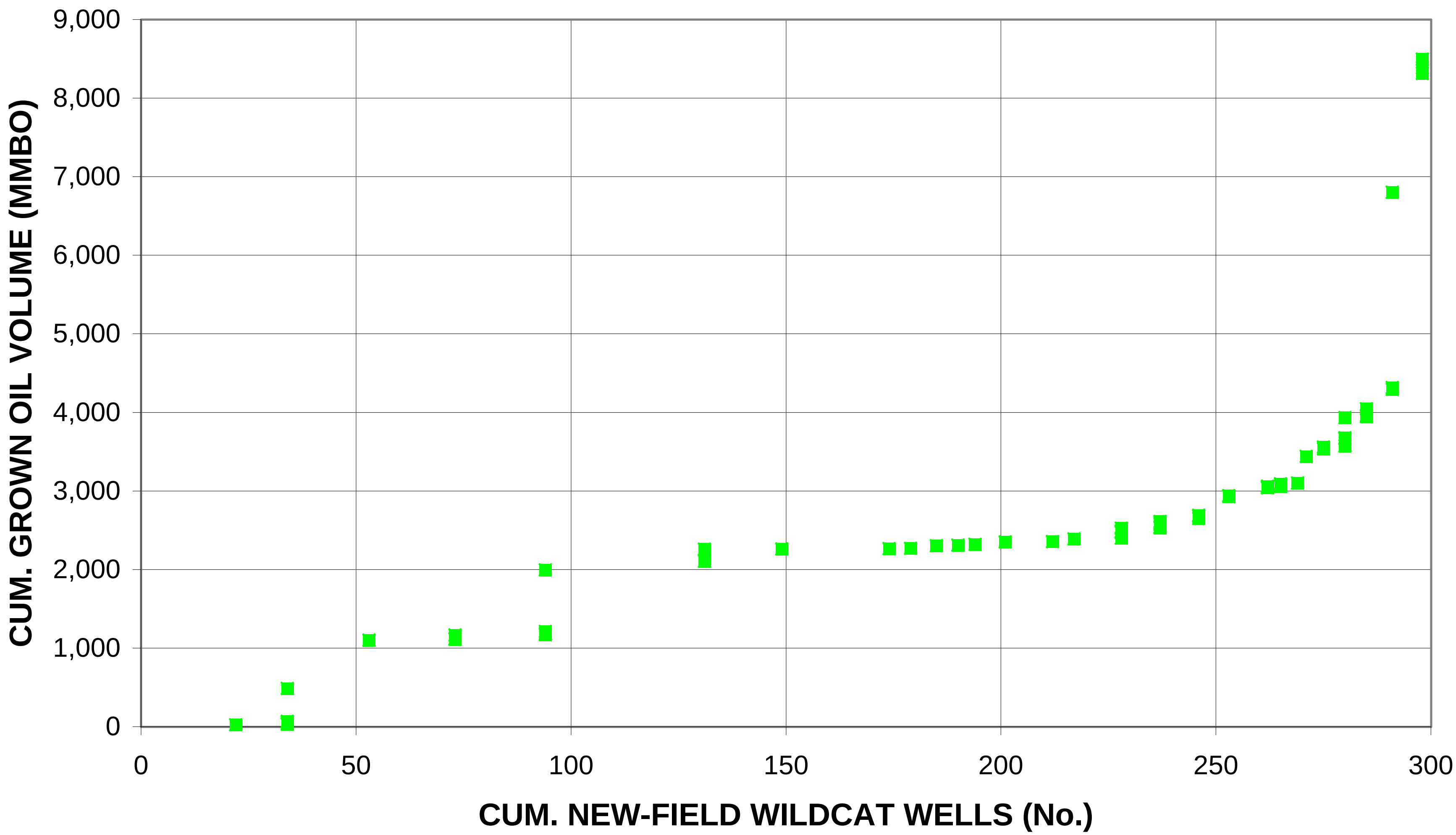

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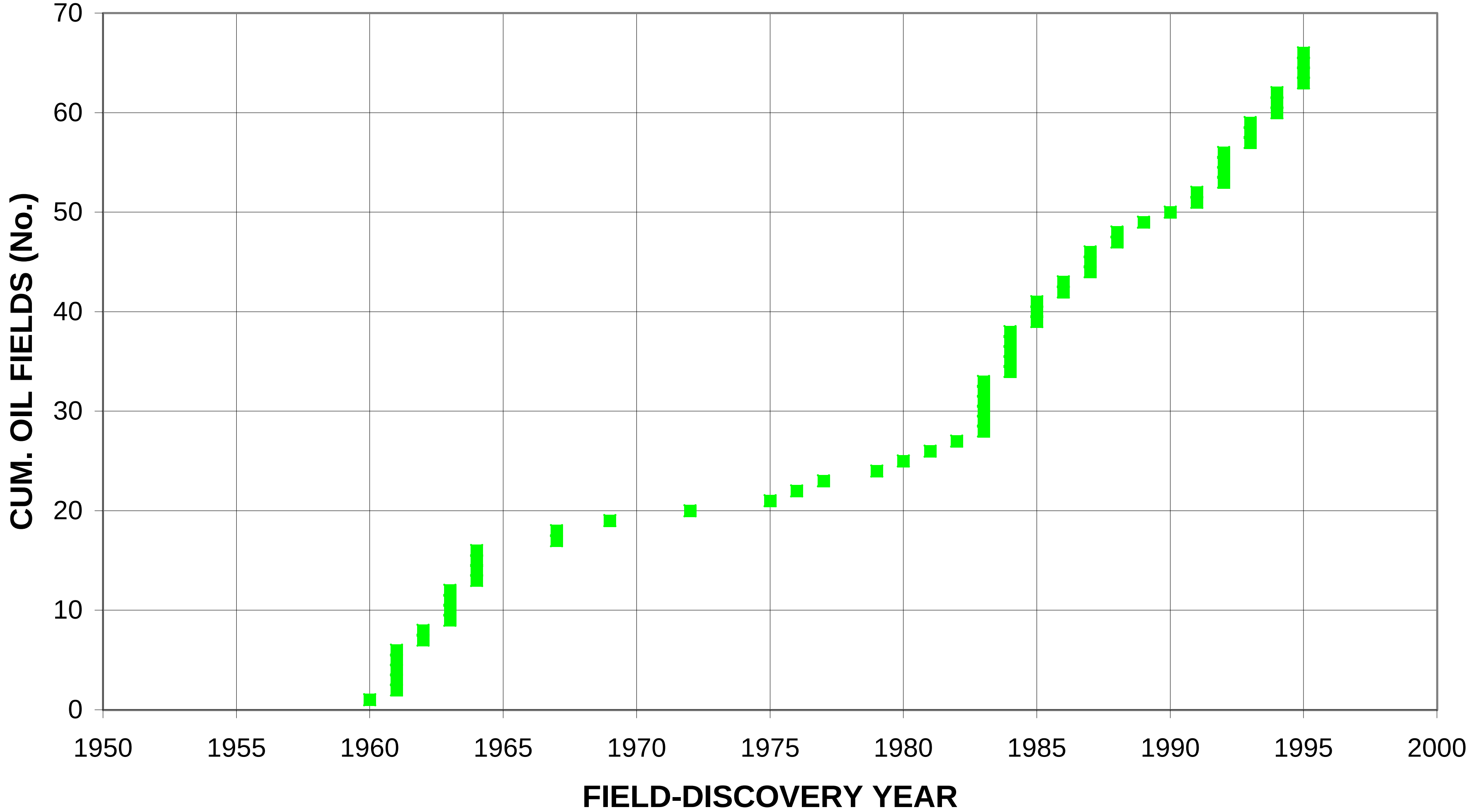
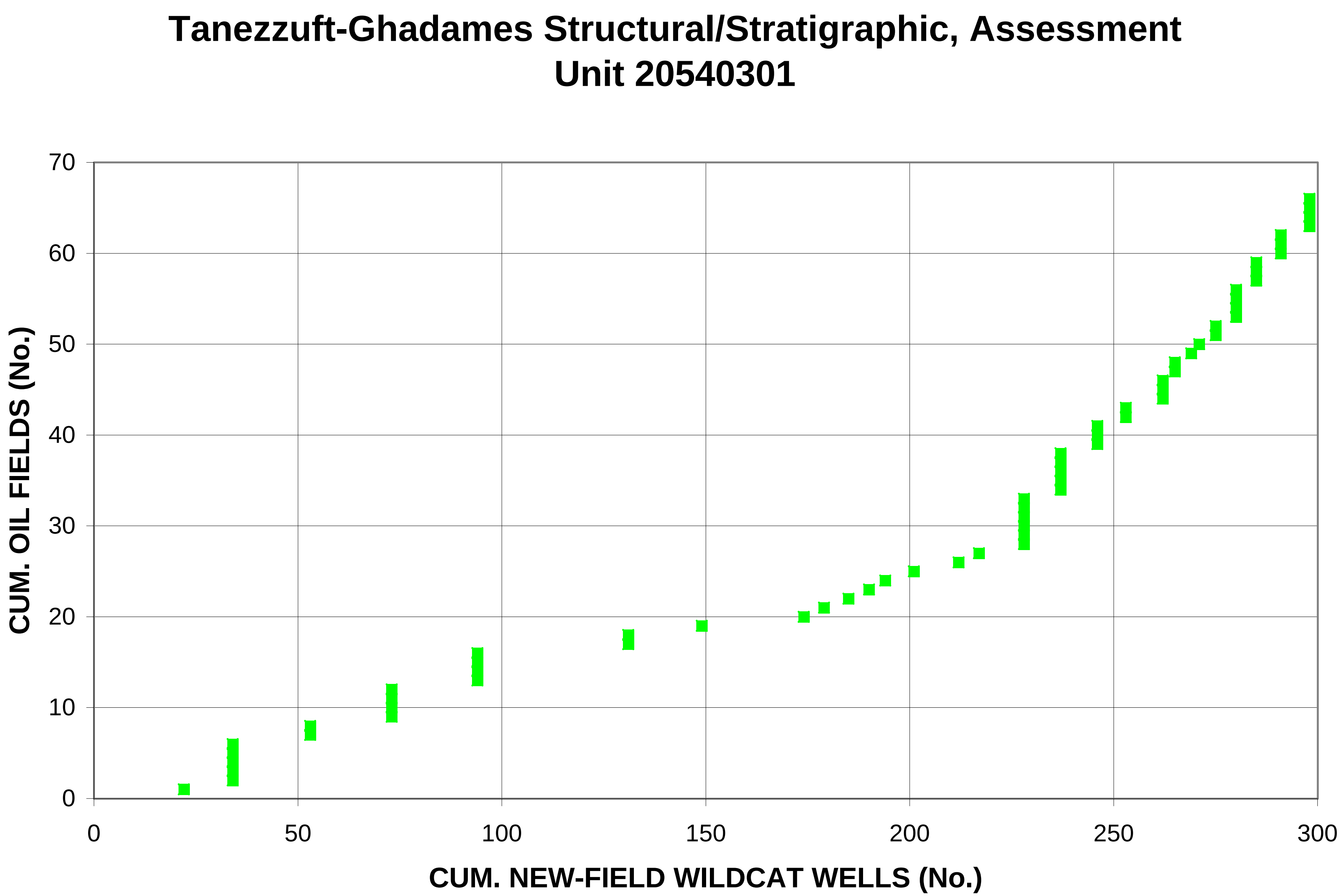
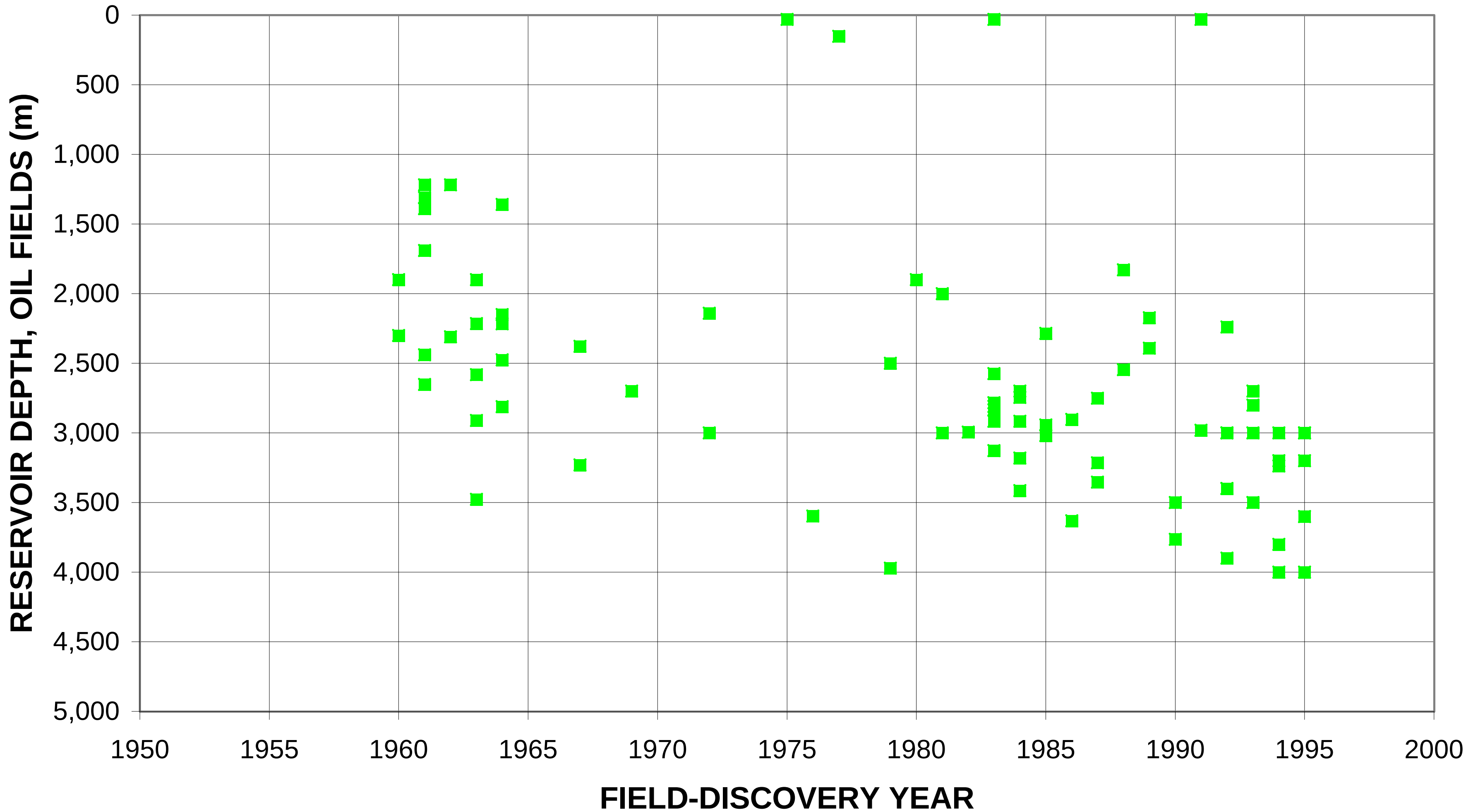
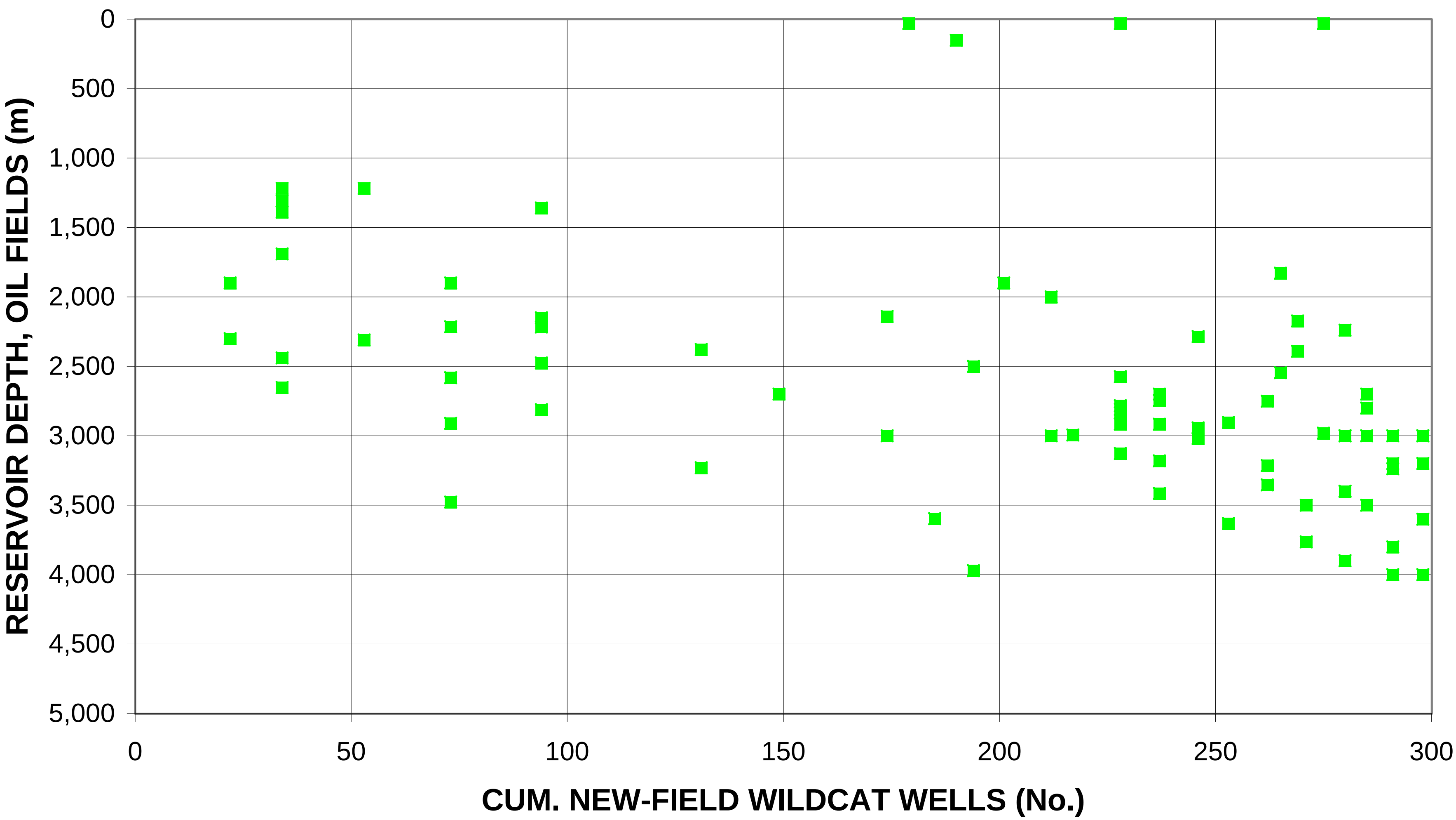



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301
CUM. OIL FIELDS (No.)
0
10
20
30
40
50
60
70
0
50
100
150
200
250
300
CUM. NEW-FIELD WILDCAT WELLS (No.)

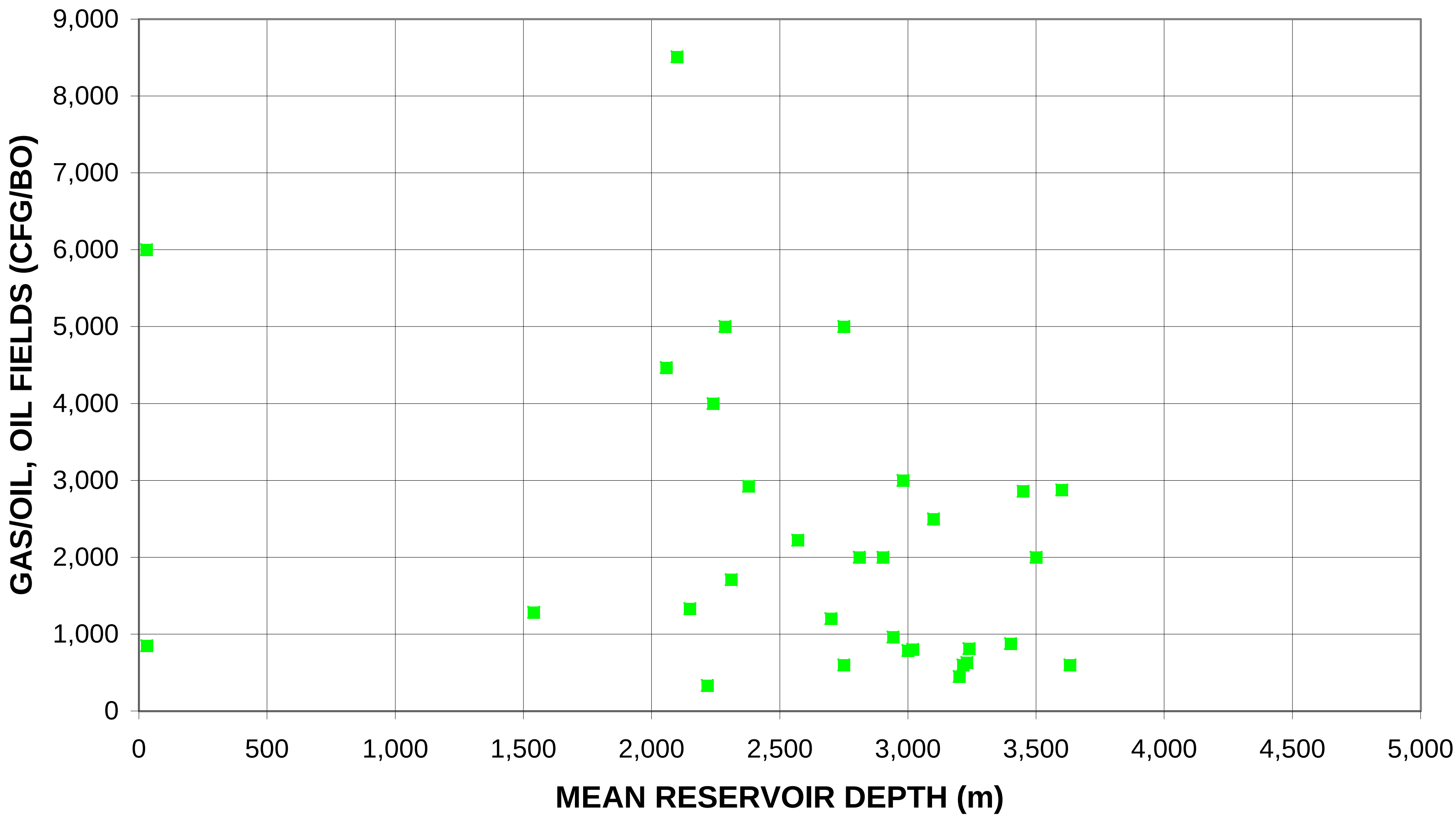
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



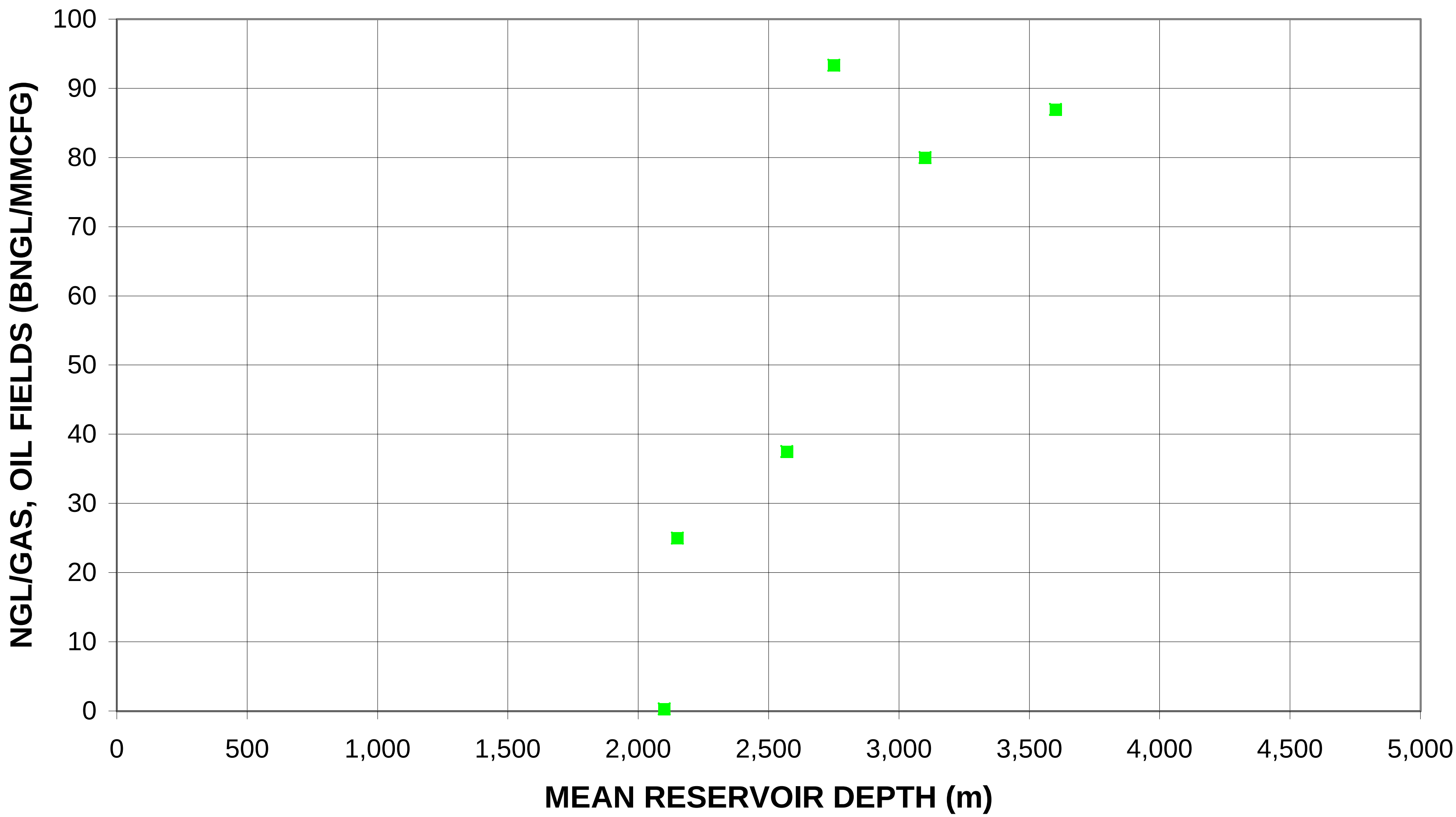
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301

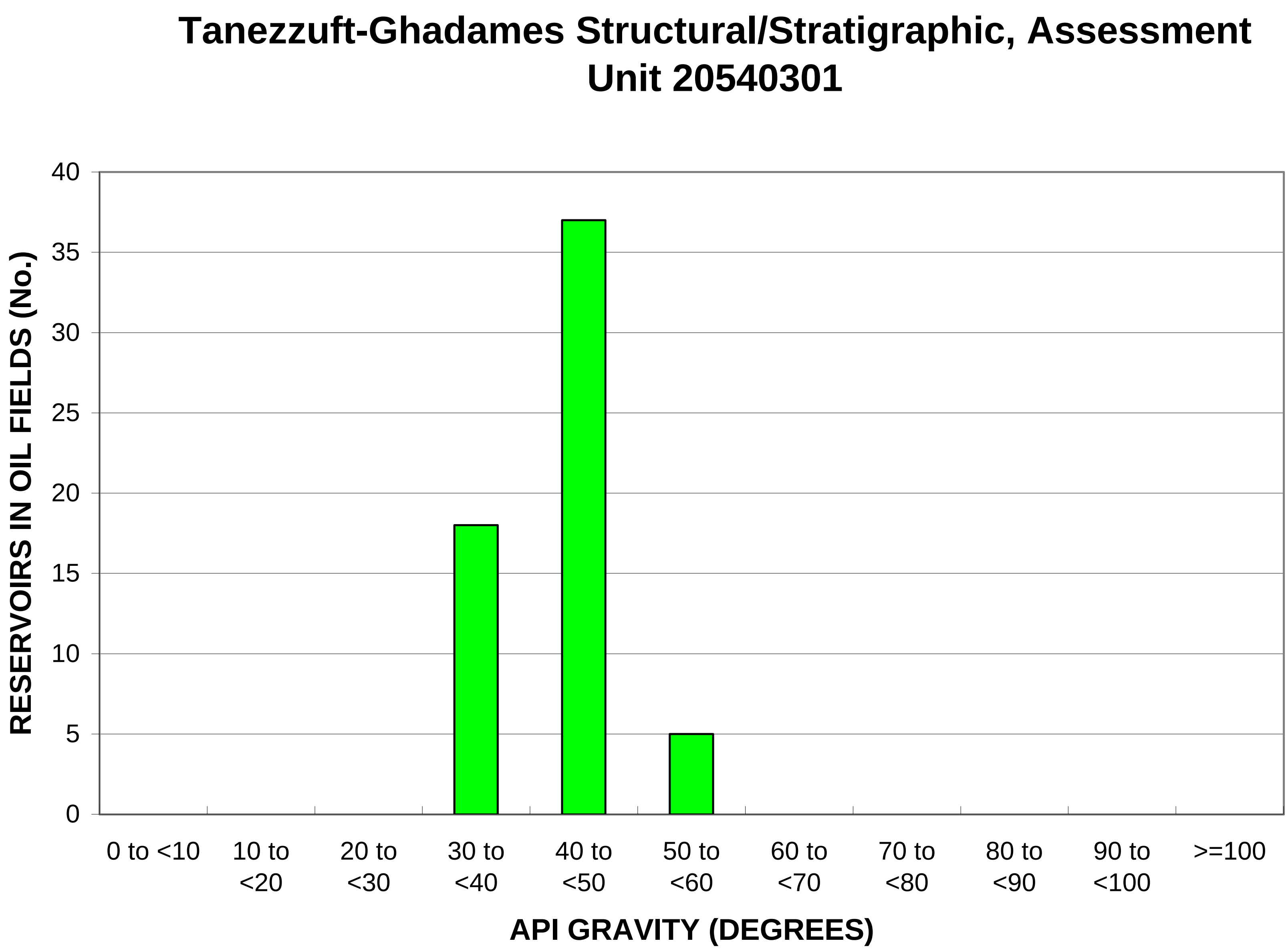


Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301

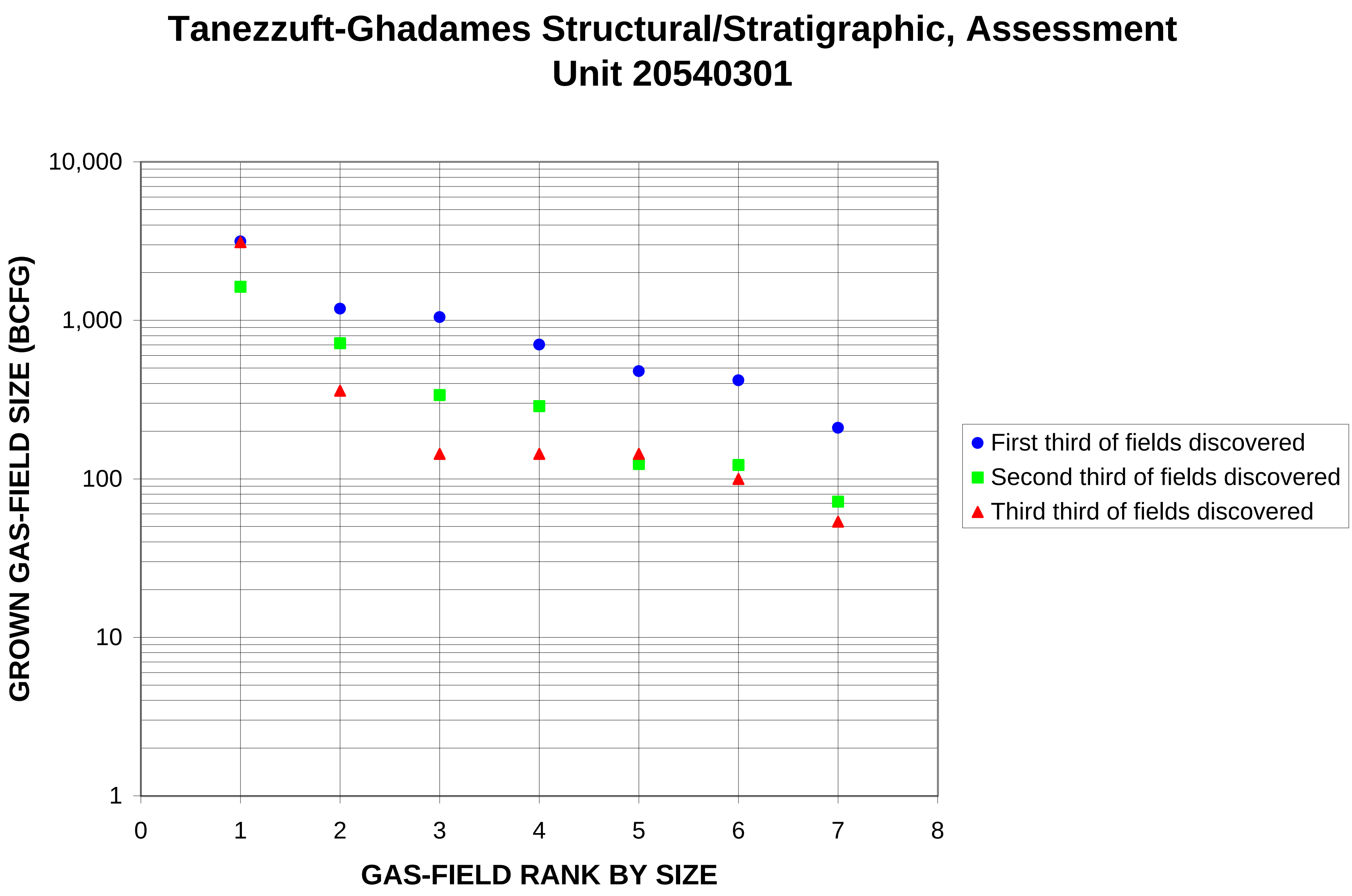


Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301





Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301
RESERVOIRS IN OIL FIELDS (No.)
0
5
10
15
20
25
30
35
40
0 to <10
10 to <20
20 to <30
30 to <40
40 to <50
50 to <60
60 to <70
70 to <80
80 to <90
90 to <100
>=100
API GRAVITY (DEGREES)



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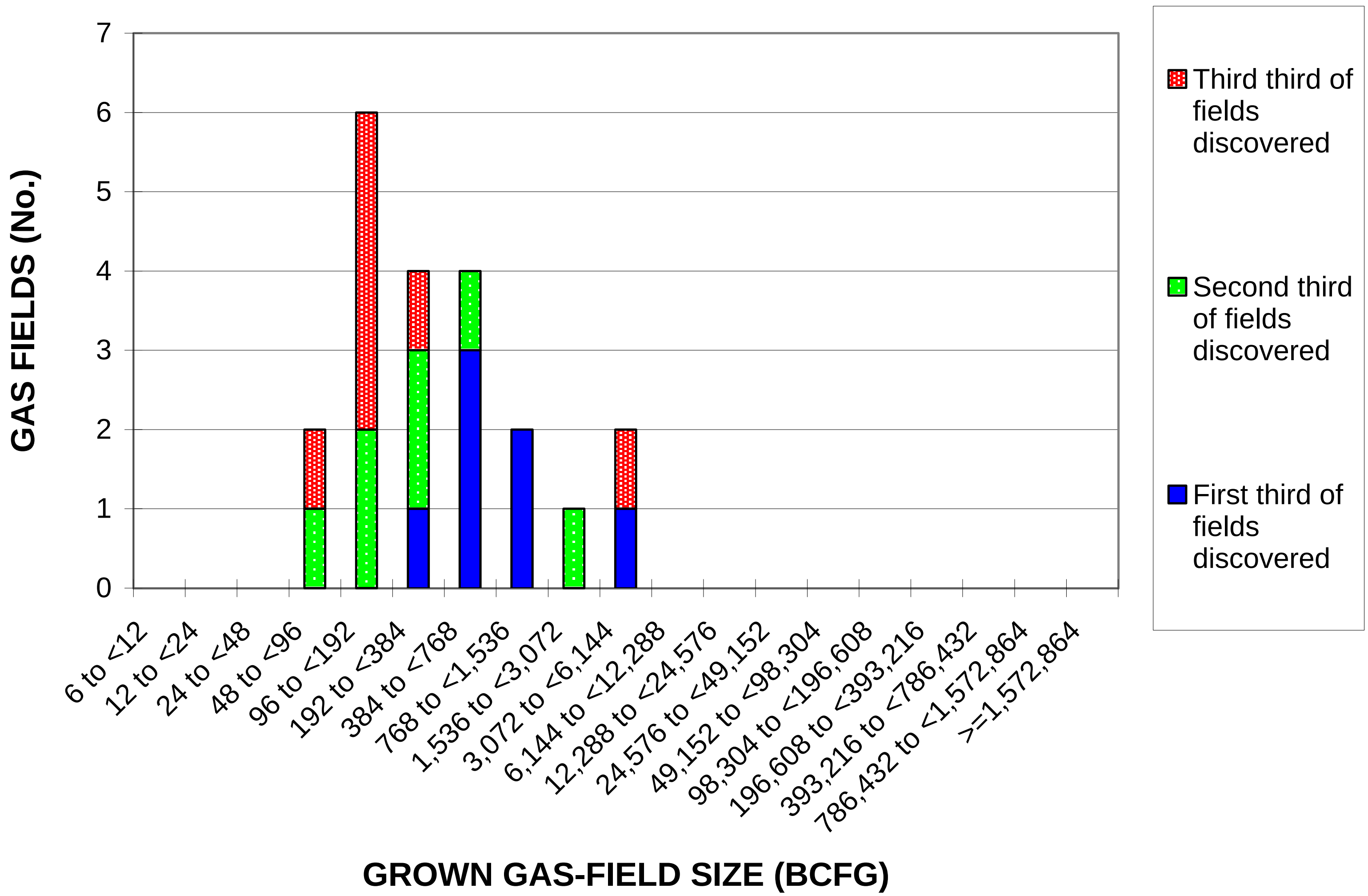
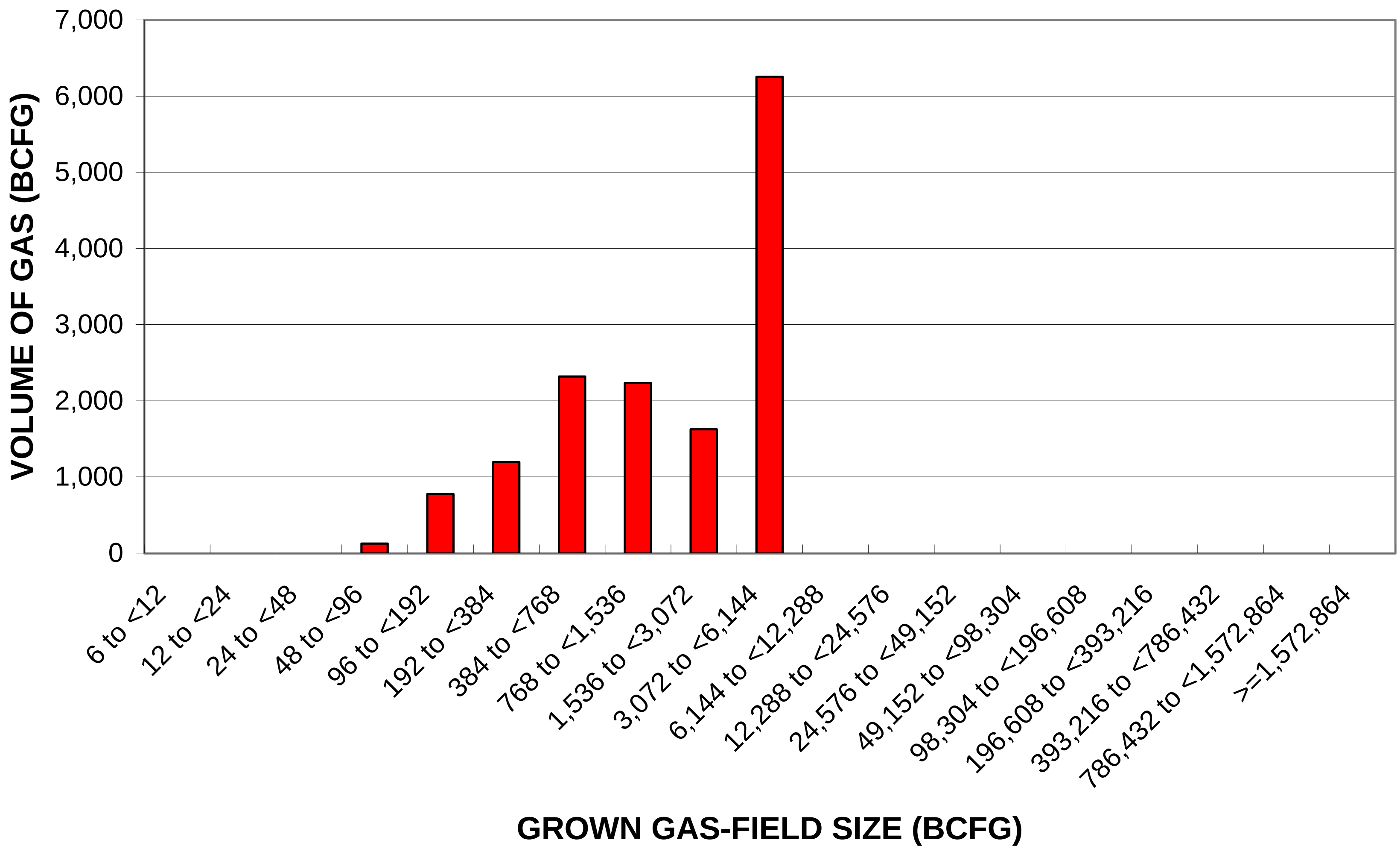
GROWN GAS-FIELD SIZE (BCFG)
10,000
1,000
100
10
1
0
1
2
3
4
5
6
7
8
GAS-FIELD RANK BY SIZE
First third of fields discovered
Second third of fields discovered
Third third of fields discovered

Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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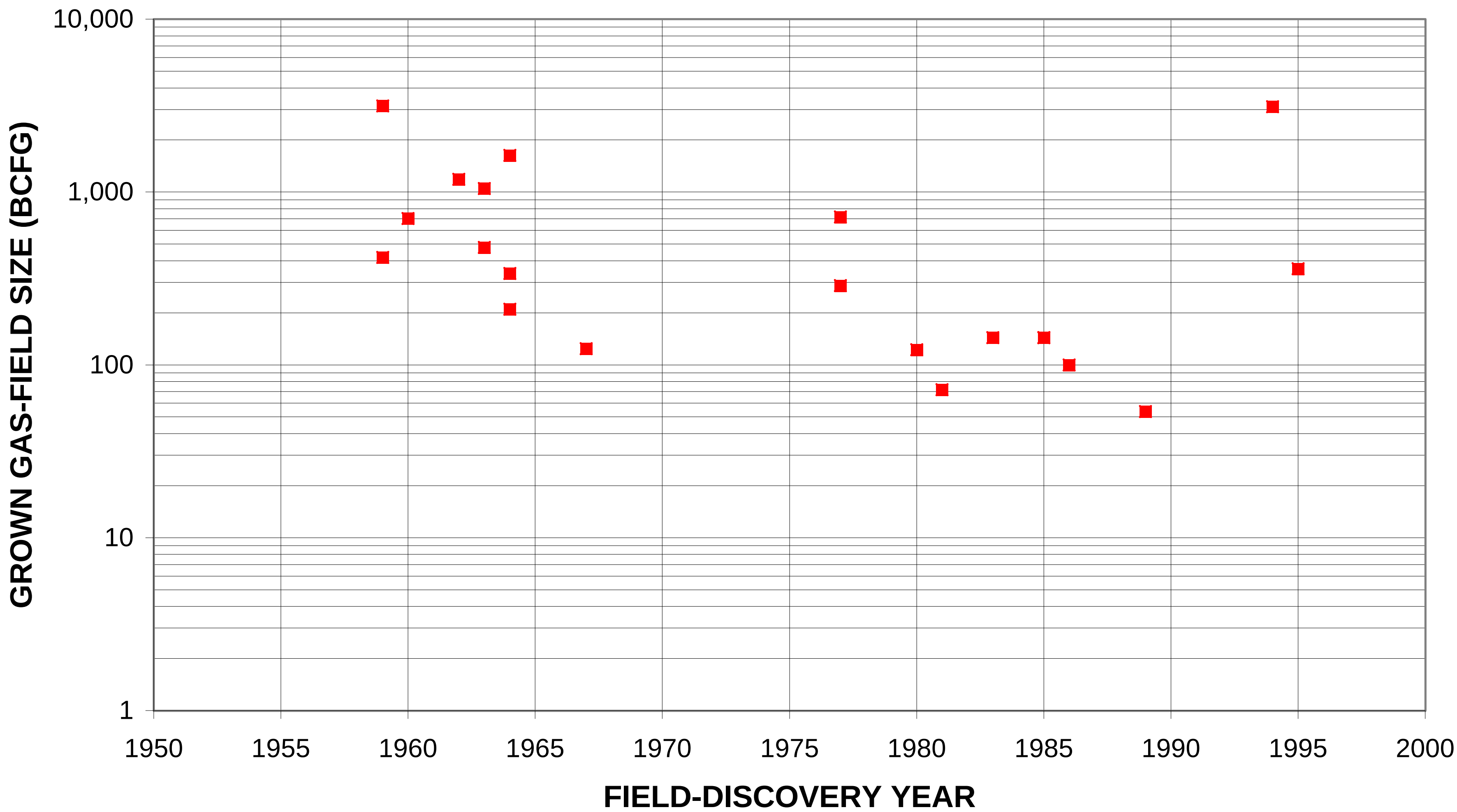
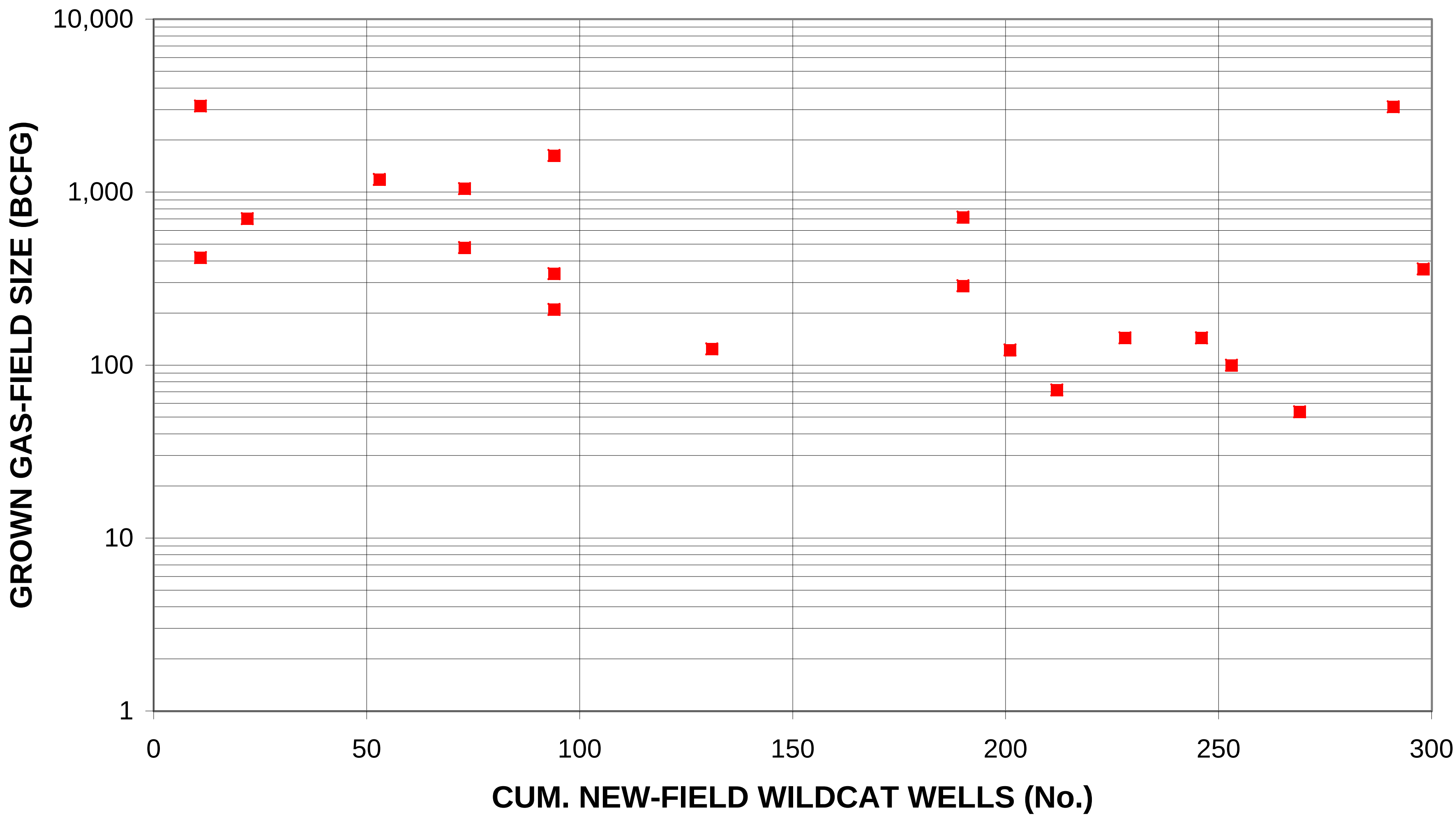
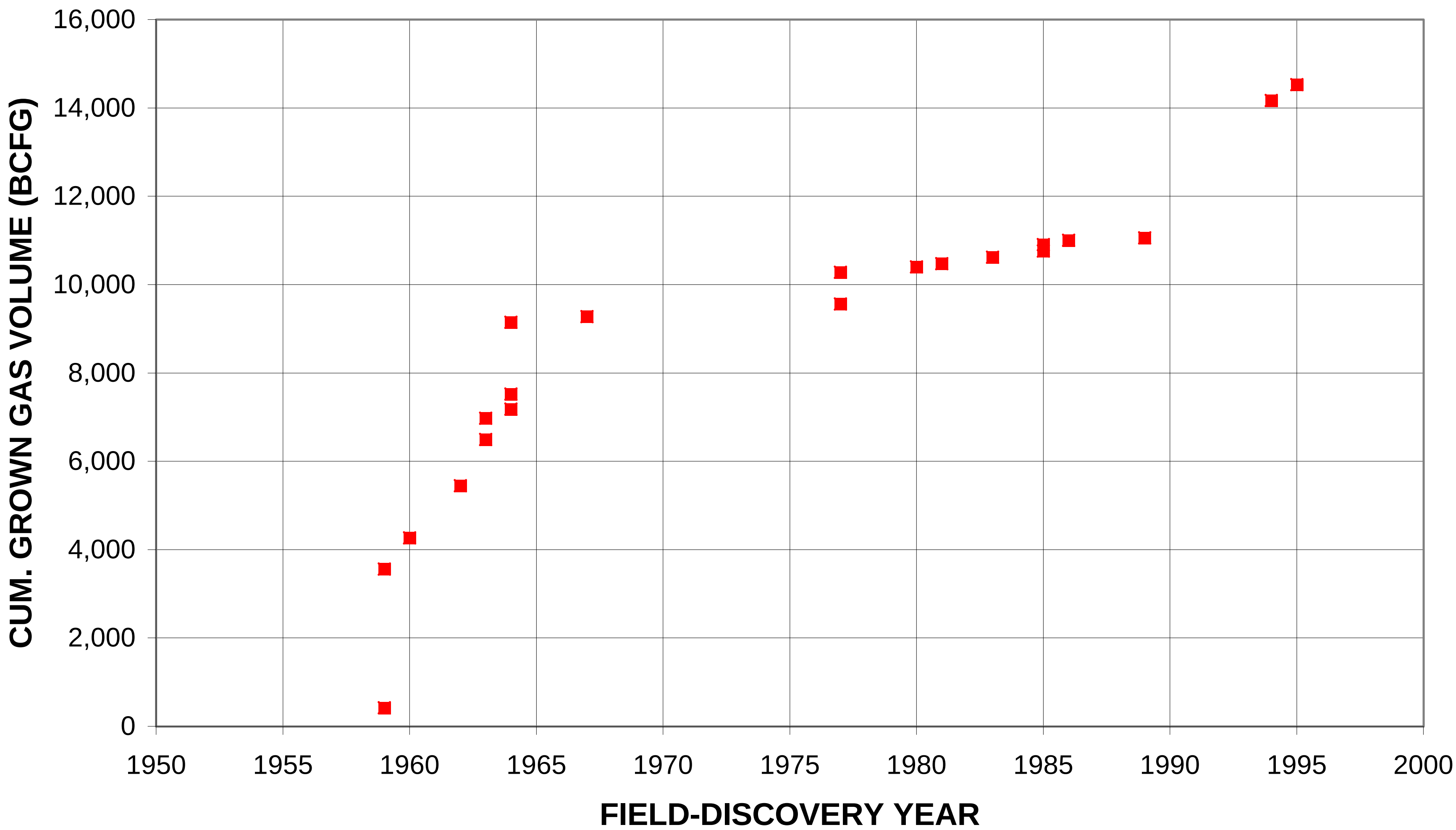


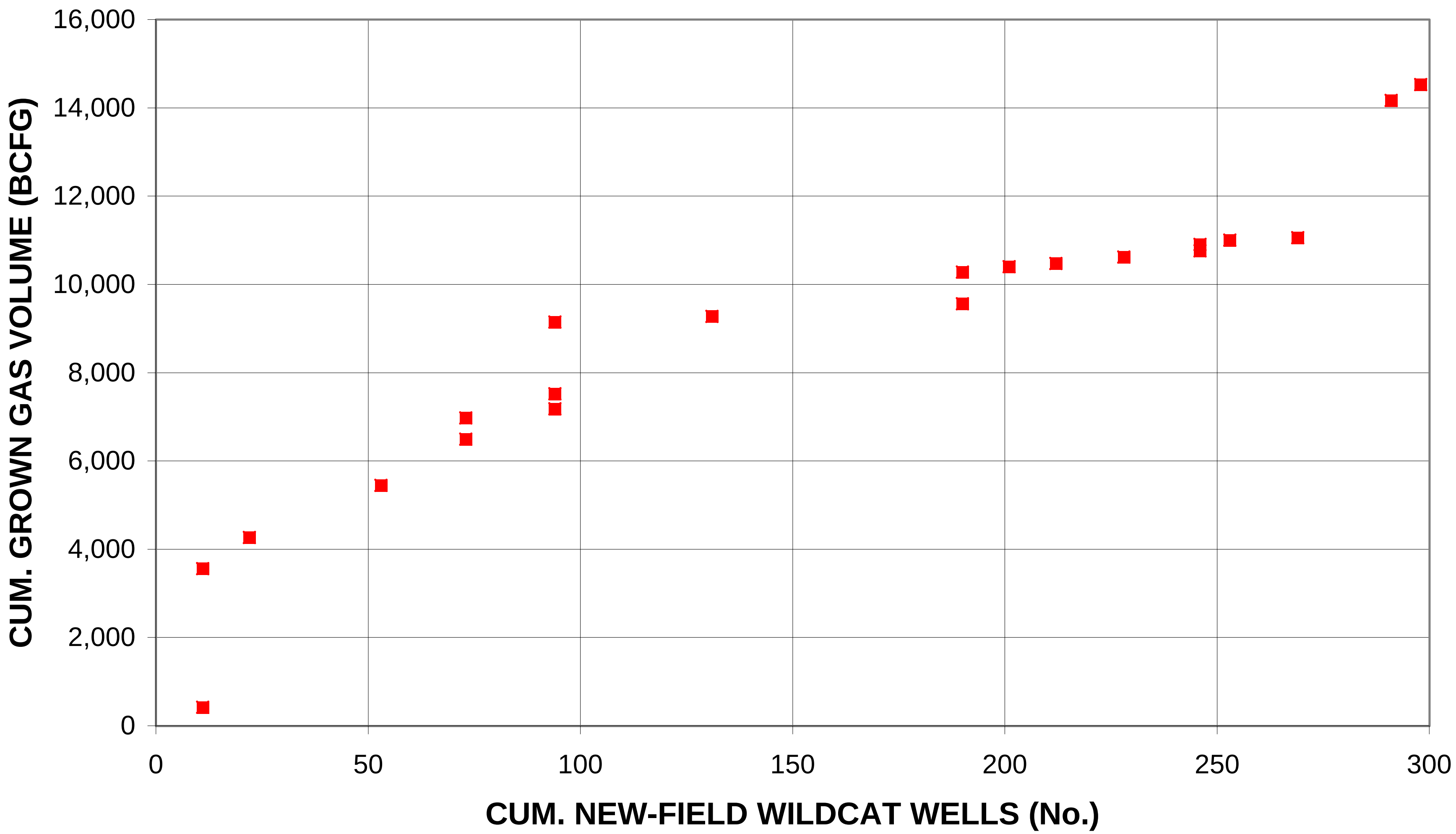
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



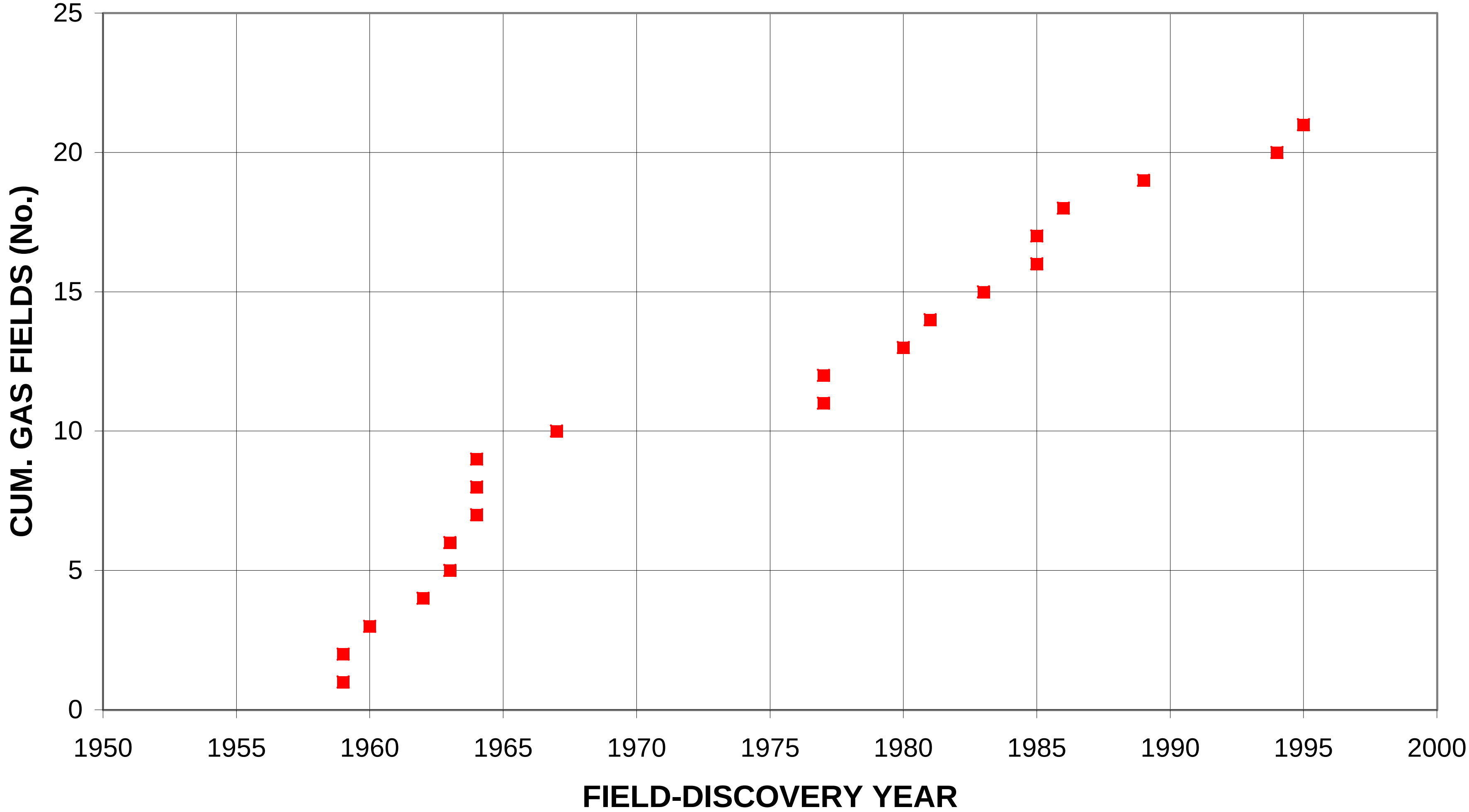
Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301



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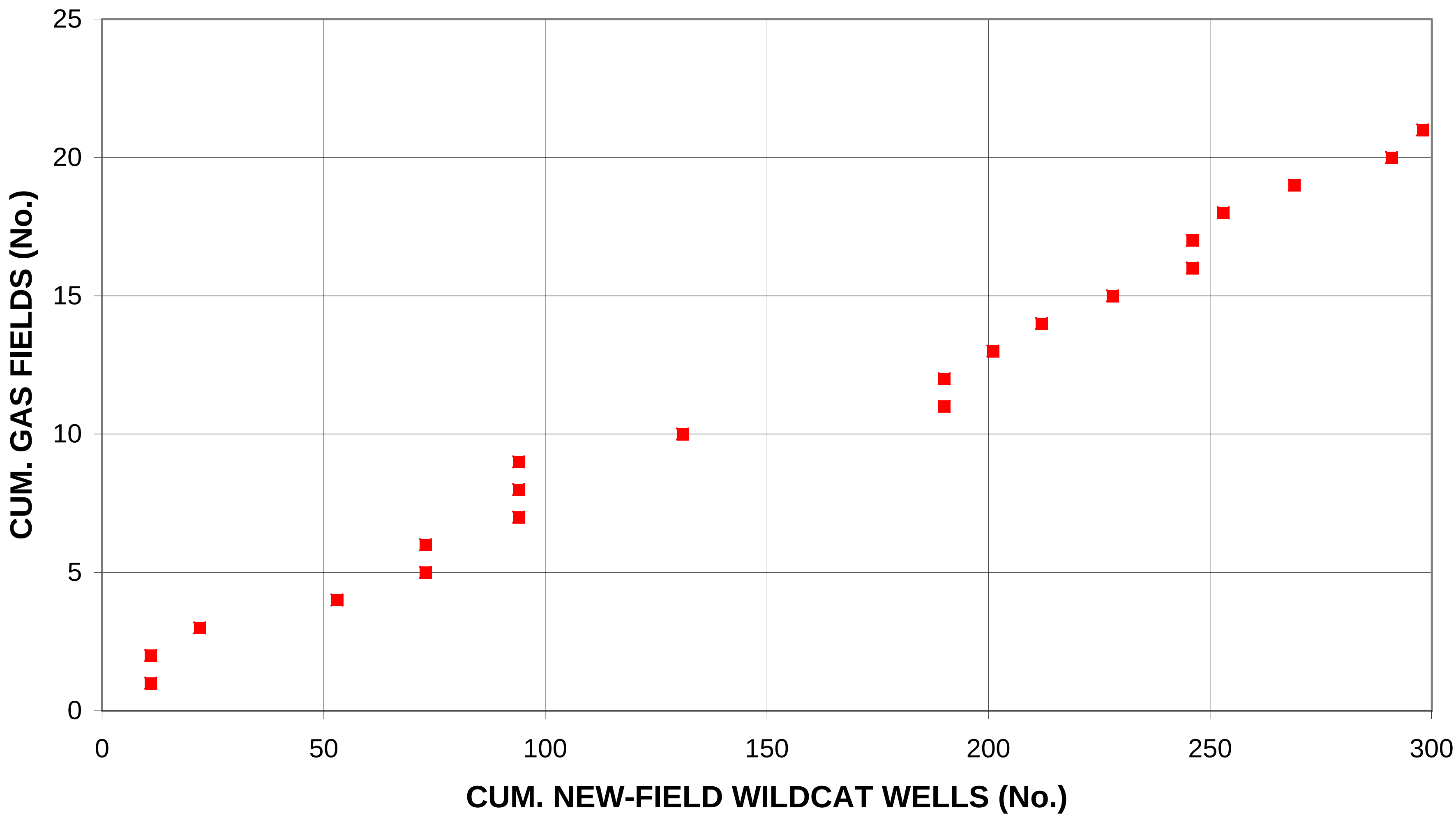
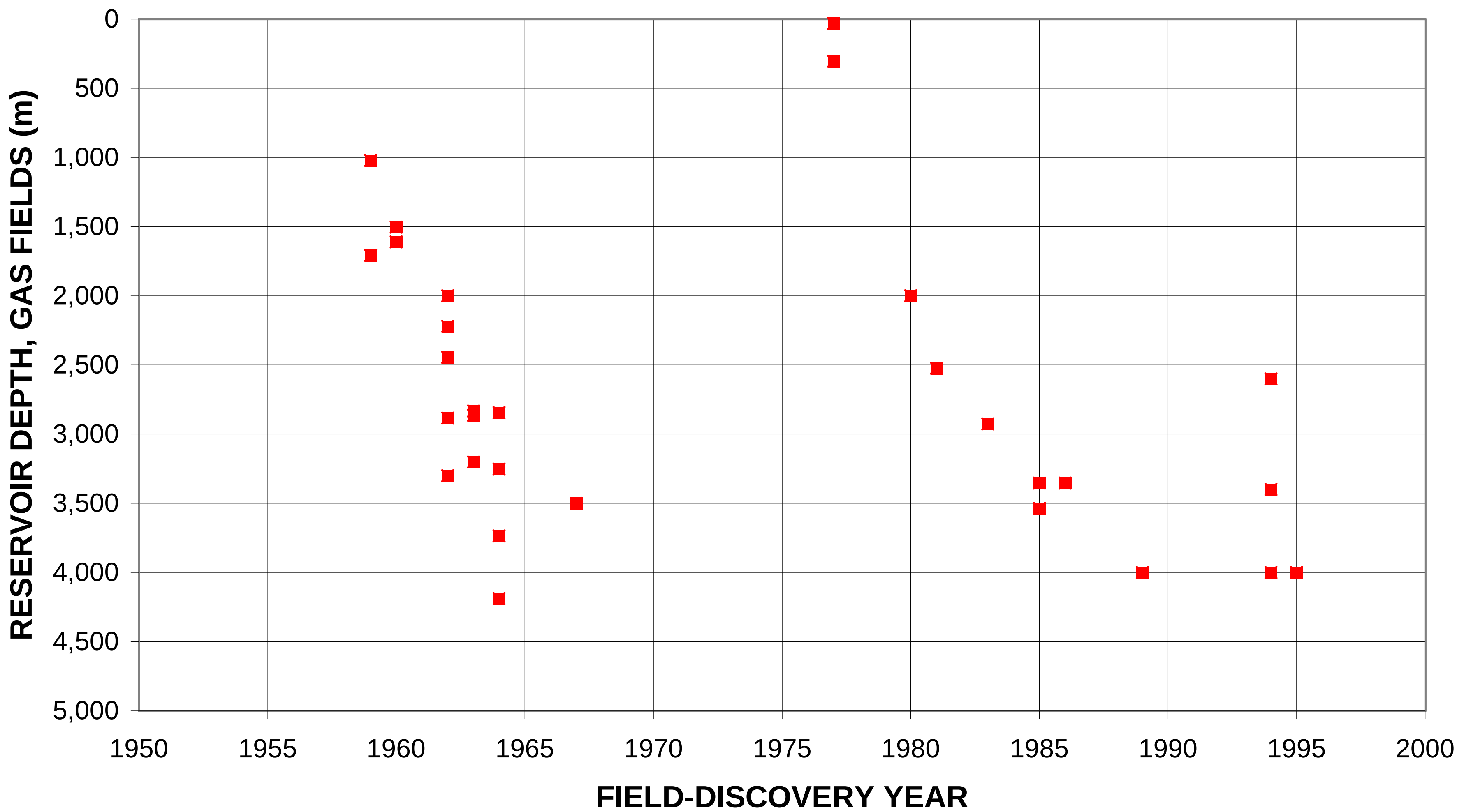
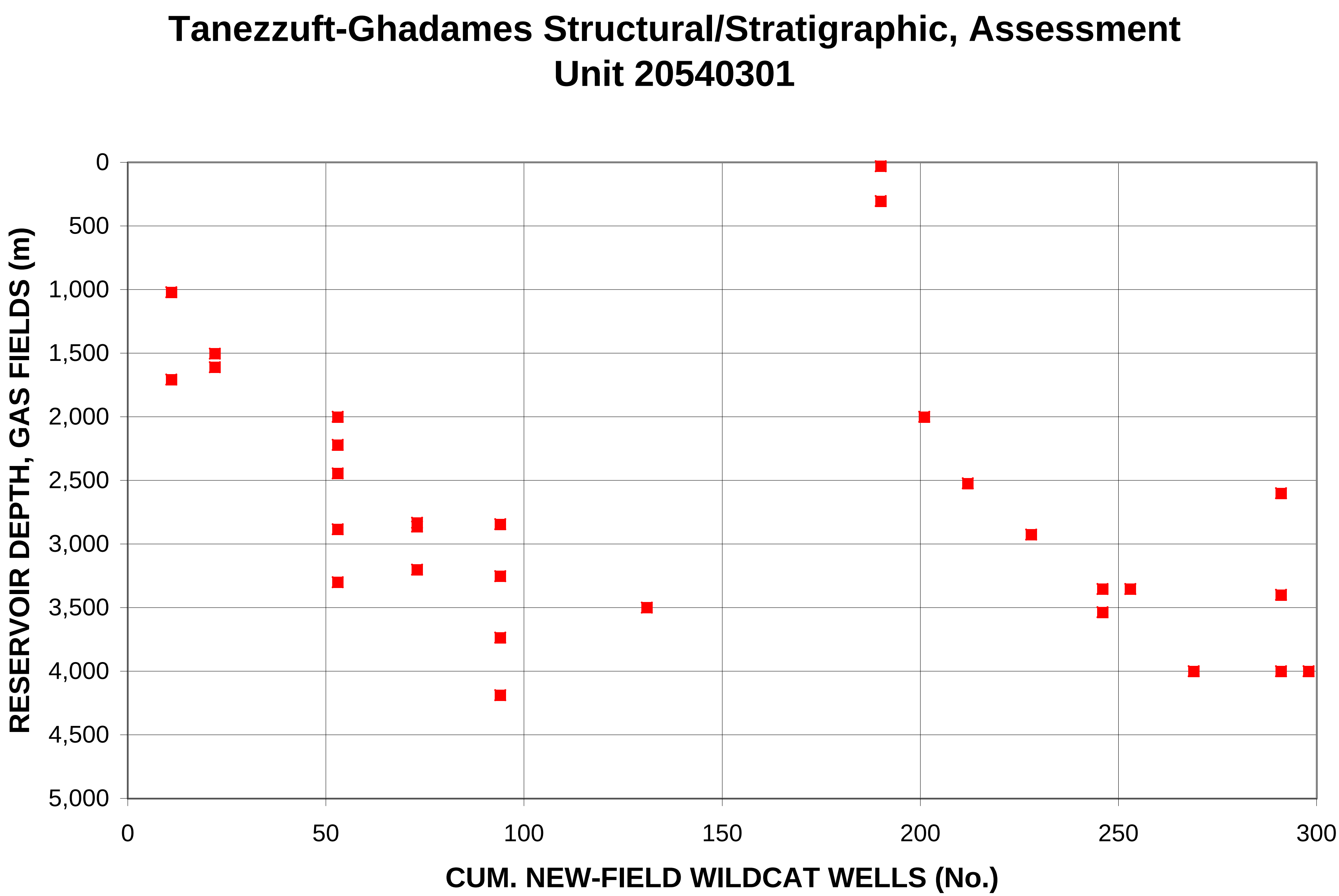


Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301




Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301
RESERVOIR DEPTH, GAS FIELDS (m)
0
500
1,000
1,500
2,000
2,500
3,000
3,500
4,000
4,500
5,000
0
50
100
150
200
250
300
CUM. NEW-FIELD WILDCAT WELLS (No.)

Tanezzuft-Ghadames Structural/Stratigraphic, Assessment Unit 20540301