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Relationship Between Rates of Penetration and Costs per Meter of Tricone Rock Bits: Cases from Southeastern Anatolia and Thrace Basins (Turkey)

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INFORMATION

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ABSTRACT

Oilwell drilling, which is a very expensive operation, requires advanced technical knowledge and technology. Choosing the most suitable drill bits for the formation conditions to be drilled, which is the most important factor in the drilling cost and the rapid completion of the well, is one of the research subjects in which a large number and detailed studies have been carried out in the last 20 years. The orientations on the subject are towards increasing the "penetration rate of drill bit" on which the drilling economy depends substantially. In addition to the mechanical properties of the rocks and the formation properties including geological conditions, the characteristics of the drill bit such as drill bit types, features, and operating parameters also affect the drilling process of a well. This study aims to examine the types, penetration rates, and costs per meter of drill bits used according to formation types in oil and gas wells in the hydrocarbon production basins of Turkey. Besides, in the study, a new global chart is presented to be used for the selection of tricone rock bits suitable for the formation to be drilled, according to the International Association of Drilling Contractors codes. Thus, in future oilwell drilling operations, a new attempt has been made to select the appropriate tricone rock bits and to penetrate in optimum conditions.

1. Introduction

Drill bits are cutting elements attached to the lowest end of the drill string, which break the rock into fragments under the influence of rotation and weight. While the drill bit is drilling the formation, the drilling fluid (mud) passes through the drill string and pushes the chips cut by the drill bit out of the well. While the weight is given to the drill bit with the help of the drill collars in the drill string; rotational movement is transmitted by the rotary table, top drive system, or mud motor in rotary drilling. The drill bit rotates with the drill string while the rotary table or top drive rotates the drill string. Although there are various types of drill bits, three-cone roller/tricone bits are generally used in oil and gas drilling wells (Fig. 1). Oilwell drilling, which is a very costly operation, necessitates advanced technical knowledge and technology. Selecting the most appropriate types of drill bits for the formation conditions to be drilled, which is the most significant factor in the drilling expenses and the quick completion of the well, is one of the research subjects in which an extensive number and detailed studies have been realized in the last 20 years.

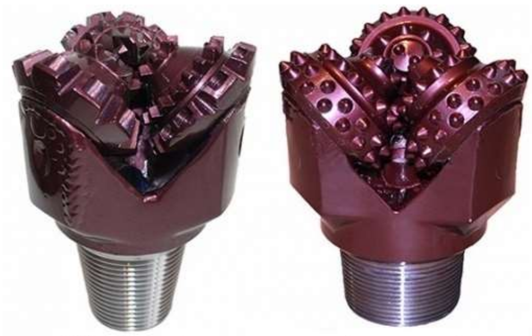

Fig. 1. Three-cone roller/tricone bit types

The orientations on the subject focus on increasing the "penetration rate of drill bit" on which the drilling economy relies mostly. As well as the mechanical properties of the rocks and the formation properties including geological conditions, the characteristics of the drill bit such as drill bit types, features, and operating parameters also affect the well drilling process. Oil and gas production areas of Turkey are located in the Southeastern Anatolia and Thrace basins (Alsharhan and Nairn, 2003; Derman, 2014) (Fig. 2). Ozdemir et al. (2021a; 2021b) have inspected the drilling engineering assessment and cost analysis of the oil and gas wells drilled in these basins in detail (Fig. 4).

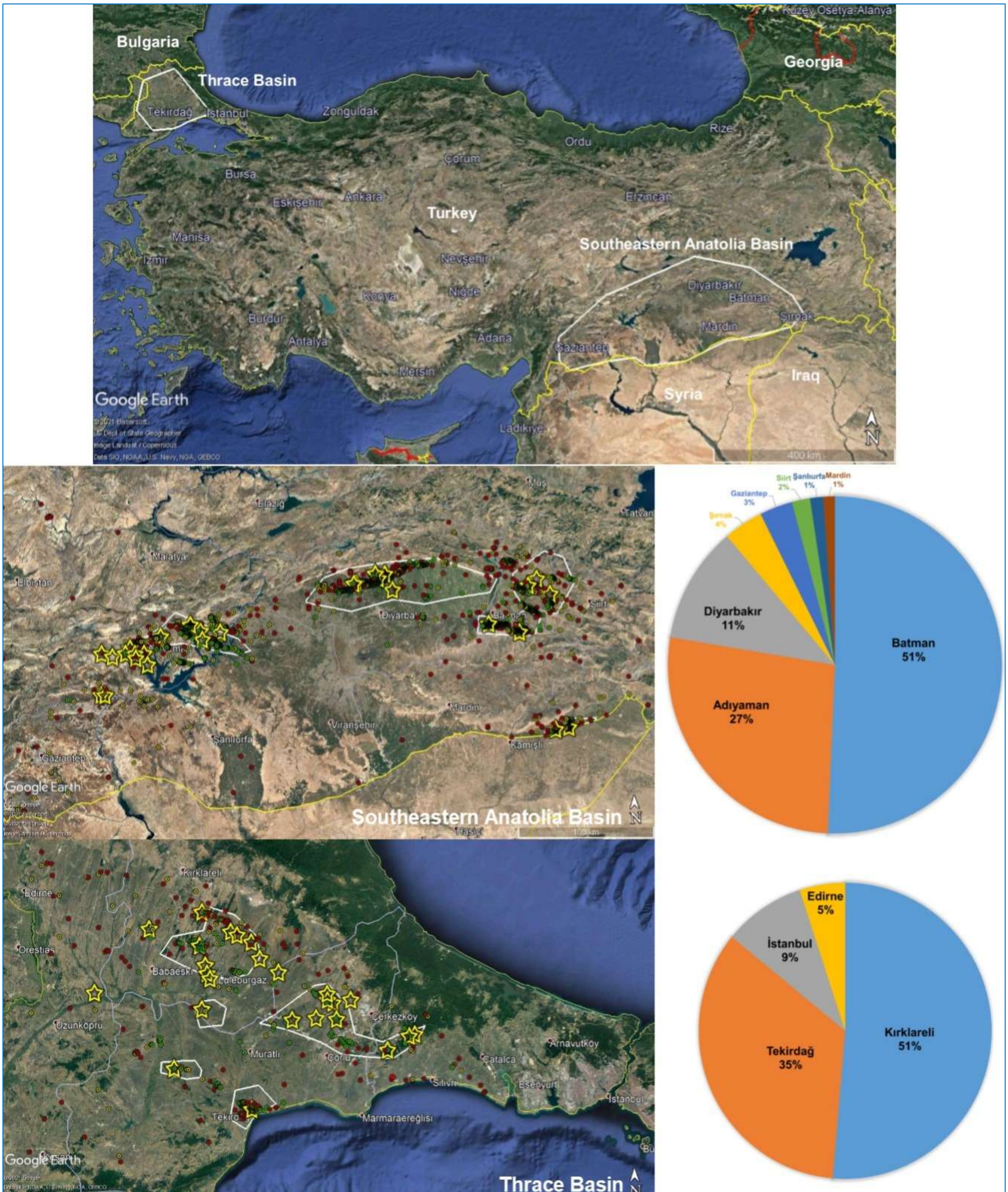

Fig. 2. Location map of Southeastern Anatolia and Thrace basins and the related data utilized. White polygons: production fields, red circle: dry well, yellow circle: well with oil/gas/wet show, green circle: production well, yellow stars: data areas

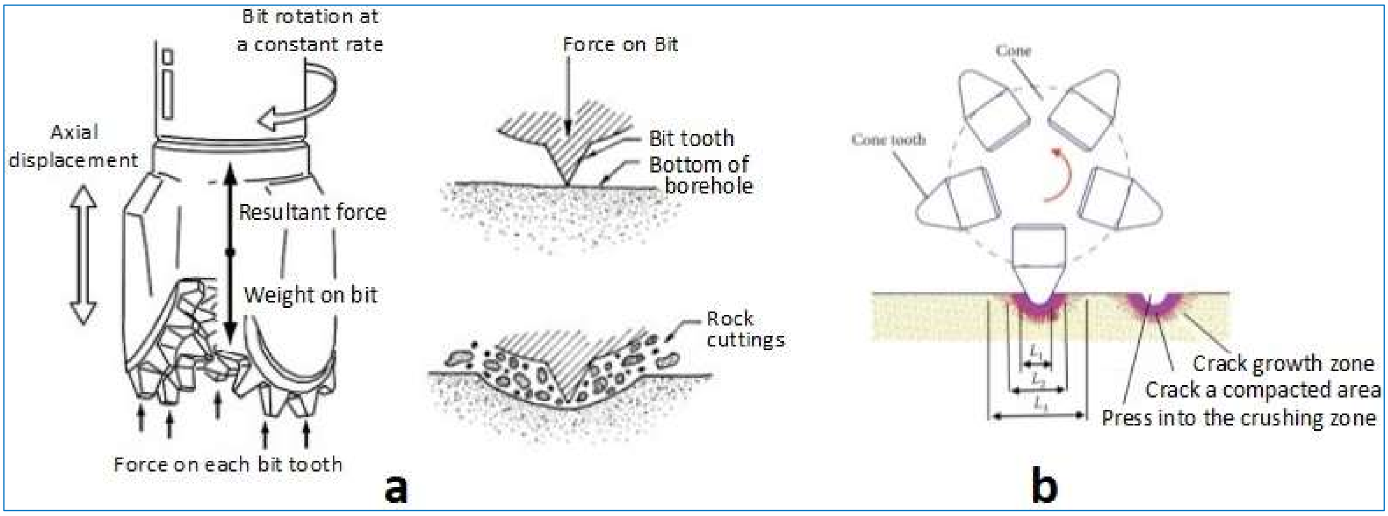

Fig. 3. The rock crushing mechanism of a tricone cone drill bit. a: steel-tooth bit, b: insert-tooth bit

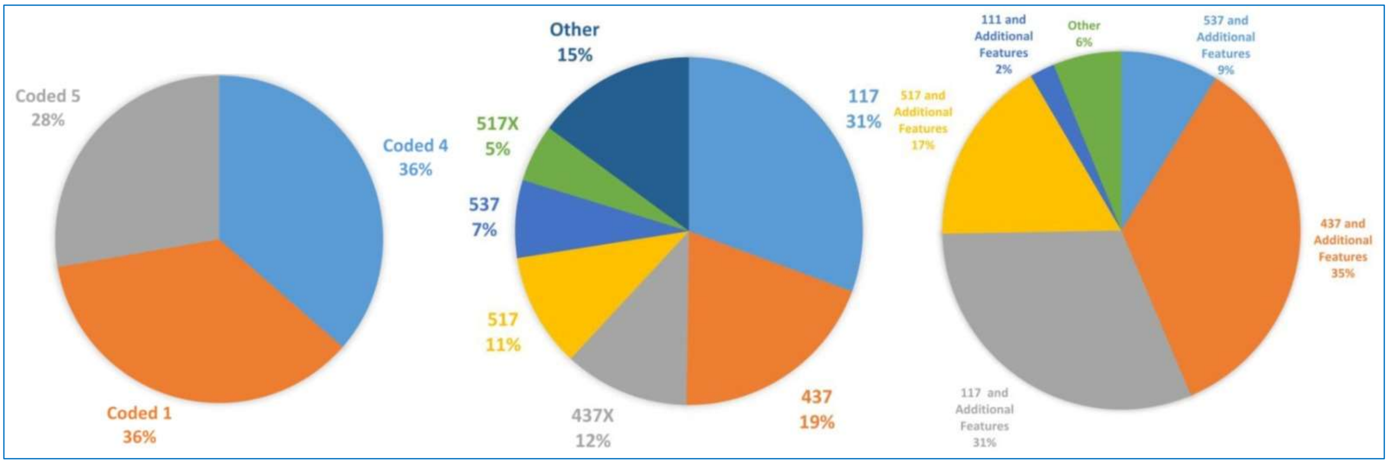

Fig. 4. Percentage distribution of tricone bits commonly used in wells according to IADC codes (modified from Ozdemir et al., 2021a)

Besides, the drillability factors of formations in the Southeastern Anatolian and Thrace basins have been determined. This research targets to go through the types, penetration rates, and costs per meter of drill bits used based on formation types in oil and gas wells in the hydrocarbon production basins of Turkey. In the study, a new global chart is presented to be used for the selection of tricone rock bits suitable for the formation to be drilled, according to the IADC codes. Therefore, in future oilwell drilling works, a new attempt has been performed to choose the suitable tricone rock bits and to make progress in optimum conditions.

2. Tricone Rock Bits Used in Onshore Oil and Gas Wells of Turkey

Tricone rock bits cut the rock by crushing and stripping under the influence of applied load (weight on bit, WOB) and rotation (Fig. 3). As the drill bit rotates at the bottom of the borehole, the cones rotate around their axes under the effect of load and rotation. They require more load and less rotation than fixed head drill bits. Since the cones rotate, the risk of jamming is lower. Tricone roller bits are divided into two as milled-tooth and TC-tooth (insert) according to the tooth type. While the teeth are produced by cutting and shaping the cones in the milled-tooth bits, the teeth are made by embedding Tungsten Carbide (TC) teeth on the cone in a certain pattern in the TC-tooth (insert) bits. Generally, milled-tooth bits are used in soft formations, and TC-tooth bits are used in hard formations.

The International Association of Drilling Contractors (IADC) coding system is used in the classification of rotary cone bits. This coding system consists of totally four characters representing the drill bit design and geological formation, with the first three characters being a number and the last character being a letter. The first three numbers indicate the series - formation type-bearing/diameter protection features, respectively, and the letter at the end indicates additional features. The IADC coding system is a 3-number coding system consisting of numbers (Fig. 5).

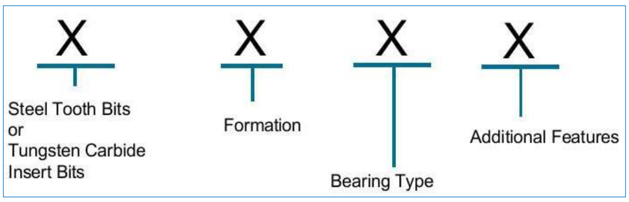

Fig. 5. The IADC coding system

Table 1. Selection chart of a tricone bit and recommended operational parameters (prepared from the product catalogs of important tricone bit manufacturers and data of this study)

IADC Code		1	2	3				
Uniaxial Compressive Strength of Formation (kg/cm²)	Formations	Series	Formation Type (soft to hard)	Bearing / Gauge	View of Cone	Tooth Type and Rock Drillability	Weight on Bit (WOB, kg)	Rotation Speed of Bit (RPM)
<400	Clay, Anhydrite, Chalk, Gypsum, Tuff, Shale, Siltstone, Anthracite, Marl, Clayey Coal, Mudstone	1 Series	1 2 3	1–7		Steel (Milled) Tooth, Easy to Drill	15 x 45 x Bit Diameter (inches)	70-120
400 to 800	Alluvium, Hard Plastic Shale, Salt, Gypsum, Anhydrite, Sand, Loose Cemented Sandstone, Greywacke, Slate, Conglomerate, Clay Limestone, Travertine	2 Series	1	1–7		Steel (Milled) Tooth, Normal to Drill	30 x 45 x Bit Diameter (inches)	60-100
800 to 1400	Dolomite, Limestone, Marble, Schist, Micaschist, Trachyte, Porous Basalt, Pegmatite, Breccia, Sandstone	3 Series	1 2	1–7		Steel (Milled) Tooth, Difficult to Drill	40 x 45 x Bit Diameter (inches)	60-80
<400	Sandy Shale, Loose Sandstone, Sand, Alluvium, Rock Salt, Talus, Travertine	4 Series	1 2 3	1–7		Tungsten Carbide (Insert) Tooth, Easy to Drill	40 x 45 x Bit Diameter (inches)	50-150
400 to 800	Alluvium, Limestone, Dolomite, Siliceous Shale, Anhydrite, Sandstone, Siliceous Siltstone, Welded Tuff, Conglomerate, Marble, Travertine	5 Series	1 2 3 4 5	1–7		Tungsten Carbide (Insert) Tooth, Normal to Drill	50 x 45 x Bit Diameter (inches)	50-120
800 to 1700	Sandy Limestone, Siliceous Limestone, Graywacke, Limestone, Dolomite, Granite, Trachyte, Gneiss, Diabase, Gabbro, Diorite, Sandstone, Peridotite, Serpentine, Syenite	6 Series	1 2 3	1–7		Tungsten Carbide (Insert) Tooth, Difficult to Drill	60 x 45 x Bit Diameter (inches)	50-120
1700 to 3200	Silex, Pyrite, Granite, Quartzite, Volcanic Conglomerate, Andesite, Basalt, Diabase, Gabbro, Diorite, Siliceous Limestone, Porphyries, Syenite	7 Series	3 4	1–7		Tungsten Carbide (Insert) Tooth, Very Difficult to Drill	70 x 45 x Bit Diameter (inches)	50-90
>3200	Silex, Pyrite, Granite, Quartzite, Andesite, Basalt, Gabbro, Chert, Radiolarite	8 Series	1 3	1–7		Tungsten Carbide (Insert) Tooth, Extreme Difficult to Drill	80 x 45 x Bit Diameter (inches)	40-80

Bearing / Gauge	
1	Standart open bearing
2	Standart open bearing, air-cooled
3	Standart open roller bearing with gauge protection
4	Sealed roller bearing
5	Selaed roller bearing with gauge protection
6	Sealed friction bearing
7	Sealed friction bearing with gauge protection

Character (Additional Features)	
A	Air application (journal bearing with air nozzles)
B	Special bearing seal
C	Center Jet
D	Deviation control
E	Extended jets (full lenght)
G	Extra gauge/steering application
H	Horizontal/steering application
J	Jet deflection
L	Lug pads
M	Motor application
S	Standard steel tooth model
T	Two cone
W	Enhached cutting structure
X	Predominantly chisel tooth inserts
Y	Predominantly conical inserts
Z	Other shape inserts

Table 2. The used data of wells in the Southeast Anatolian Basin

Formation	Lithology	Well number used data	Total footage (m)	IADC code	Average WOB (ton)	Average rotation speed (RPM)	Average mud weight (lb_m/cu ft)	Average circulation flow rate (gpm, gal/min)	Average pump pressure (psi)	Average net penetration rate (m/h)	Average cost per meter ($)
Lower Germav	Shale, marl	15	2720	437, 437X, 437W, 517, 517X, 617, 115	8	108	72.5	368	1635	3.53	165.58
Upper Germav	Shale, sandstone, marl, clayey limestone	23	13753	117, 137, 437, 437X, 517, 537	6	123	70	411	1561	7.73	111.98
Garzan	Limestone, bioclastic limestone	10	2078	437X, 517, 537, 437, 117	6	103	74.5	413	1651	4.12	231.83
Gercüş	Conglomerate, shale, siltstone, sandstone, evaporite	32	23732	117, 437Y, 135, 137, 437X, 115, 545, 131, 437, 517	7,5	116	68.5	448	1408	6.03	94.04
Germav	Shale, sandstone, marl, limestone	18	13992	117, 135, 137, 415, 437, 437X, 437Y, 515, 517X, 517W	10	123	72	582	1940	4.34	151.05
Hoya	Limestone, dolomite, marl, chert, locally dolomitic clay	40	14743	111, 115, 117, 117M, 135, 137, 445, 437, 437X, 437Y, 515, 517X, 545	8	109	68	419	642	5.87	94.54
Karababa + Karaboğaz	Clayey limestone, limestone, chert	17	1476	135M, 437, 437X, 517, 537, 515, 537, 537M, 537X	11	102	67	407	1863	2.36	414.41
Kastel	Shale, marl, conglomerate, sandstone	20	6181	137, 425X, 437, 437X, 515, 517, 517X, 537, 537X	11	148	75	585	1967	2.40	263.28
Kayaköy	Dolomite, anhydrite, gypsum, shale	5	3153	137, 437, 517	9	115	70.5	517	1205	3.33	240.93
Midyat	Limestone, chert, shale, gypsum	6	3644	111, 415X, 435, 437, 437X, 515, 535X	12	121	72	691	1729	3.96	160.56
Sayındere	Clayey limestone	22	3990	117, 137, 437, 437X, 437W, 517, 517M, 517X, 517W, 537, 537M, 537X	10	108	74	444	1808	3.61	304.88
Şelmo	Shale, conglomerate, claystone, sandstone, siltstone, clay	24	9090	111, 114, 115, 115M, 131, 135, 137, 137M, 435, 435X, 437X, 437Y, 515M, 537	5	98	70.5	562	839	4.46	125.99

Table 3. The used data of wells in the Thrace Basin

Formation	Lithology	Well number used data	Total footage (m)	IADC code	Average mud weight (lb_m/cu ft)	Average pump pressure (psi)	Average WOB (ton)	Average rotation speed (RPM)	Average net penetration rate (m/h)	Average circulation flow rate (gpm, gal/min)	Average cost per meter ($)
Danişmen	Claystone, siltstone, sandstone	18	13392	137, 437X, 537, 437, 217, 517, 117	82.5	1710	6.5	105	8.78	422	98.24
Ergene	Sandstone, conglomerate, claystone	34	26144	137, 135, 117, 437, 115, 135M, 217, 111, 515, 537, 127, 311	72.5	1112	5	99	11.89	472	70.46
Osmancık	Sandstone, shale, siltstone, claystone	5	4194	117, 137, 437, 437W, 517, 517X	72.25	1697	6	102	7.61	425	66.75
Kırcasalih	Conglomerate, sandstone, claystone	4	2189	135, 137, 437, 515	67	1271	5	100	13.34	523.58	40.74

In this coding system, the first number represents the series of the drill bit. Numbers between 1 and 3 in this number, which can take values from 1 to 8, represent standard drill bits. 1 represents the largest tooth structure, manufactured for the softest formations, while 3 represents standard milled-tooth bits with the smallest tooth, manufactured for the hardest formations. The values on numbers 4 and 8 in the first row of the coding represent drill bit with recessed thread. 4 represents the large-toothed insert drill bits made for the softest formations and 8 represents the smallest-toothed insert bits manufactured for the hardest formations. The second digit, which can take values from 1 to 4, represents the bit type and indicates which hardness (1 softest, 4 hardest) the bit was manufactured for, regardless of whether it is steel or insert tooth. The 3rd number in the coding reflects the characteristic of the bit bearing. It ranges from 1 (the most basic type of bearing) to 7 (the most complex type of bearing). The last character is used to identify additional features.

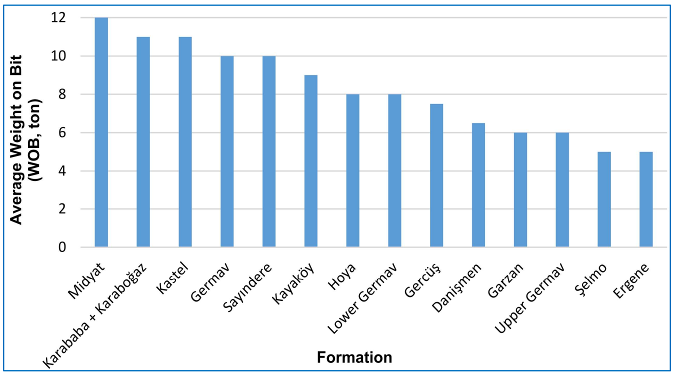

Fig. 6. Average weights on bit in the formations in the hydrocarbon production basins of Turkey

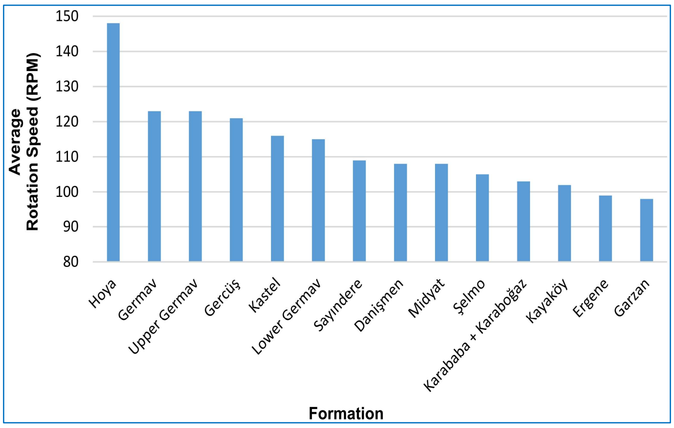

Fig. 7. Average rotation speeds of tricone bits used in the formations in the hydrocarbon production basins of Turkey

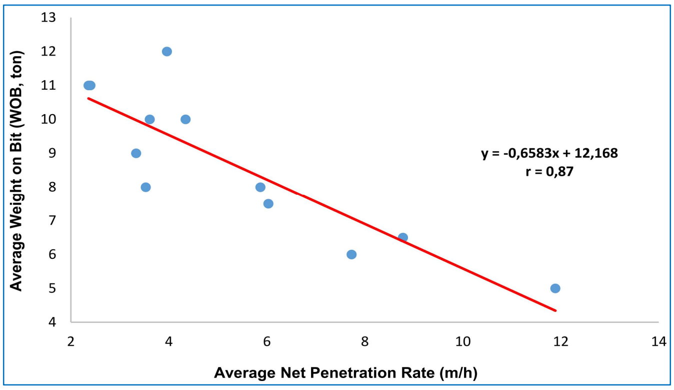

Fig. 8. Relationship between average weight on bit and average net penetration rate

For example: 437X: Tungsten carbide (insert) tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts (see Table 1).

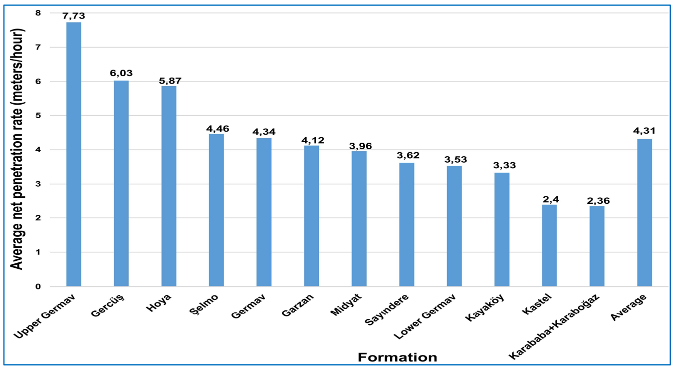

Fig. 9. Average net penetration rate of tricone bits used in the formations in the Southeastern Anatolia Basin

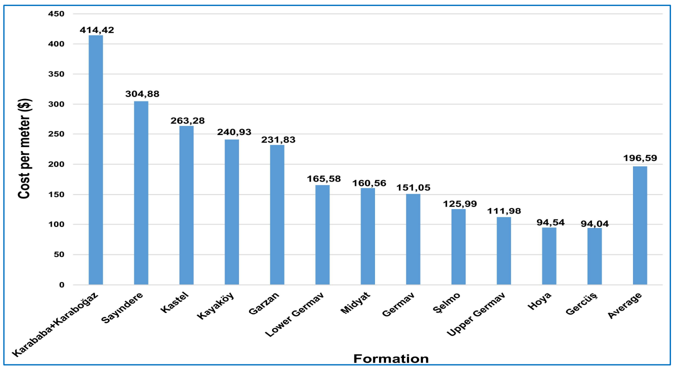

Fig. 10. Cost per meter of tricone bits used in the formations in the Southeastern Anatolia Basin

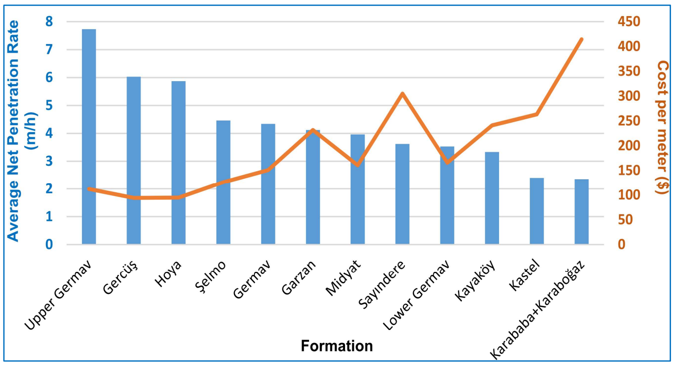

Fig. 11. Relationship between cost per meter and average net penetration rate

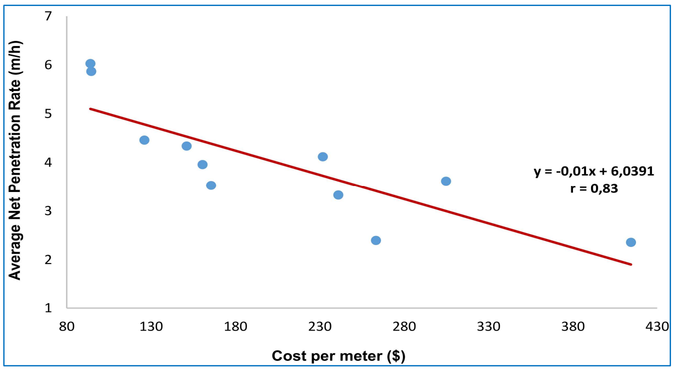

Fig. 12. Relationship between average cost per meter and average net penetration rate

Manufacturers' specifications include bit model code, IADC code, diameter range, recommended weight on bit and rotation speed of bit, and other specific structural properties and operational parameters. Appropriate bit type and operating parameters can be selected using the information provided by the bit manufacturers (Table 1). The most commonly used bits according to IADC codes in formations in Turkey's oil and gas fields are given in Fig. 4.

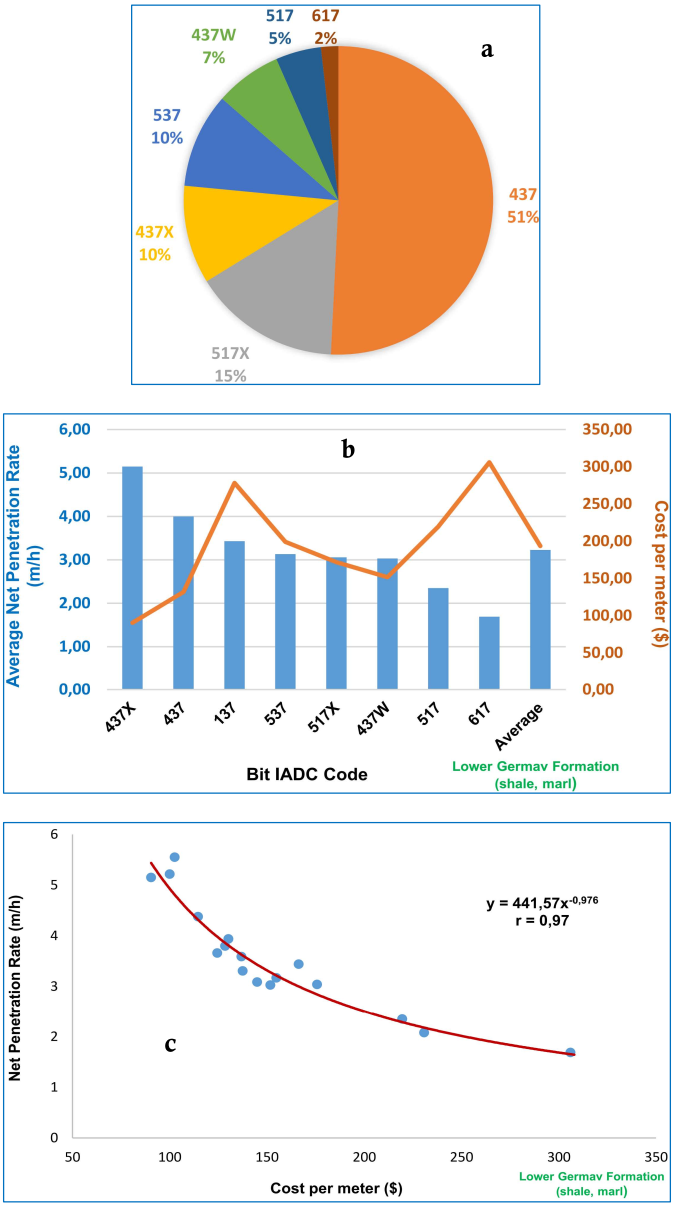

Fig. 13. Tricone rock bit types, rates of penetration and costs of meter used in the Lower Germav Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

According to the rock bit types used, it is understood that the formations in Turkey's oil and gas fields are predominantly formed of formations which easily and normally drillable. Accordingly, the commonly preferred milled-tooth (steel) tricone bits in easily drillable formations are 117 (milled-tooth, sealed friction bearing with gauge protected) and 111 (milled-tooth, standard open bearing) IADC coded bits (Fig. 4). In difficult drillable formations, it is seen that generally milled-tooth bits are not preferred.

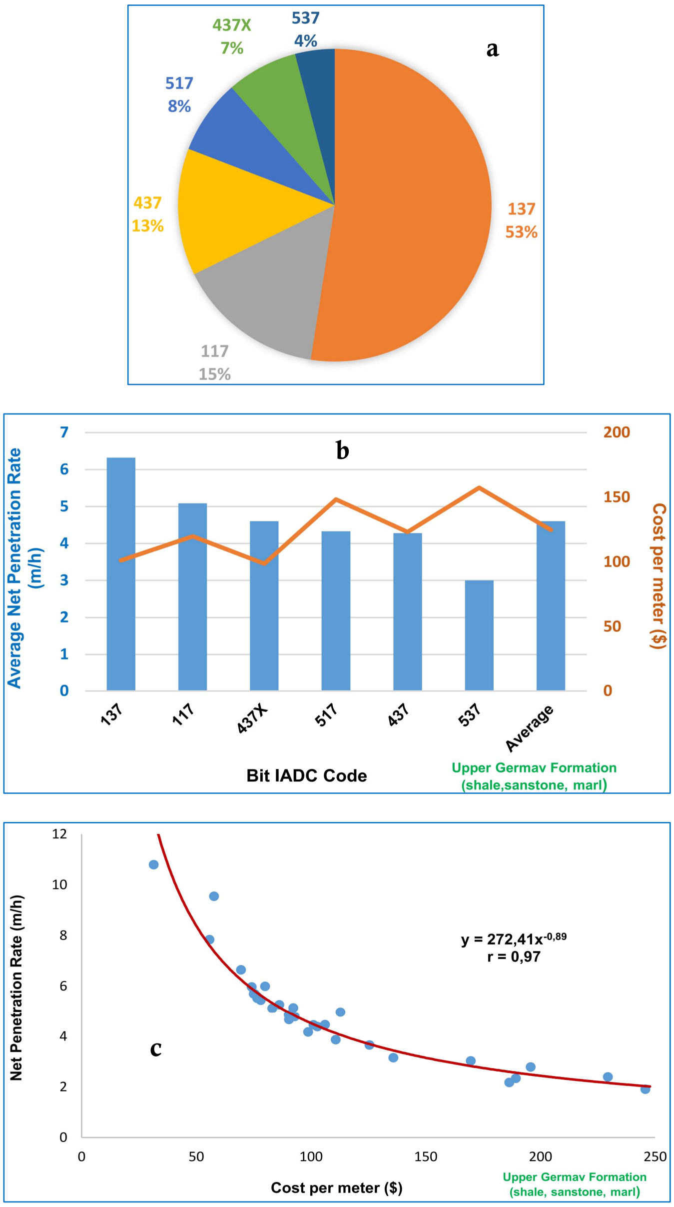

Fig. 14. Tricone rock bit types, rates of penetration and costs of meter used in the Upper Germav Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

The commonly preferred insert-tooth bits for easily drillable formations are 437 (insert-tooth, sealed friction bearing with gauge protection) and 437X (insert-tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts) IADC coded bits. The mostly preferred insert-tooth bits in normal drillable formations are 517 and 537 (insert-tooth, sealed friction bearing with gauge protection) and 517X (insert-tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts) IADC coded bits (Fig. 5). The tricone bits data used in the examined oil and gas drilling wells within the scope of this study are given in Fig. 1 as well as Tables 2 and 3 (Also, see Appendices 1 and 2).

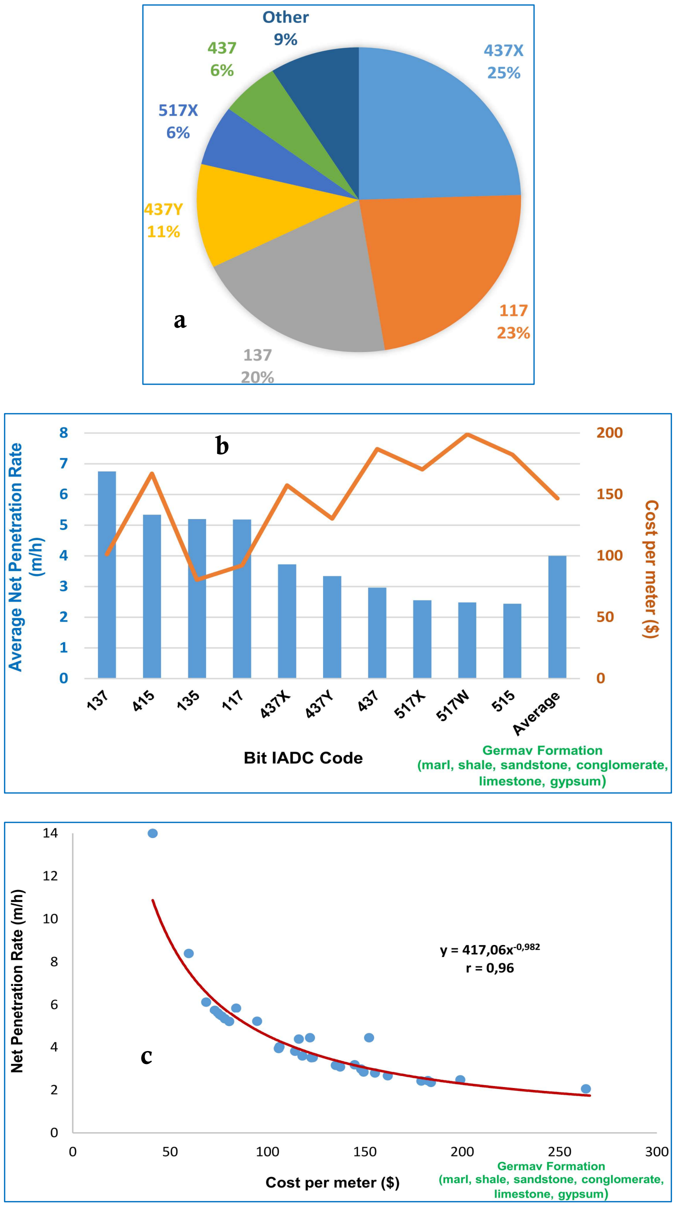

Fig. 15. Tricone rock bit types, rates of penetration and costs of meter used in the Germav Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3. Performance and Cost Evaluation of Tricone Rock Bits

Discovery and drilling of hydrocarbon-producing fields are both expensive and difficult phases of the petroleum industry. When the annual reports of major oil companies are examined, it is seen that drilling operations constitute almost 40% of the total cost of oil and gas producing fields. Drilling costs can be categorized under two main groups; tangible and intangible costs. Since most intangible costs are unavoidable, tangible costs are taken into account when making economic optimization. Tangible costs mostly include operating costs (costs incurred while the bit is running). Therefore, while optimizing the tangible costs, the cost needs to be calculated based on the drilling time. An accurate drilling speed estimation model will result in successful cost optimization as the running time is directly related to penetration rate and range of penetration rate (Ozbayoglu and Omurlu, 2005).

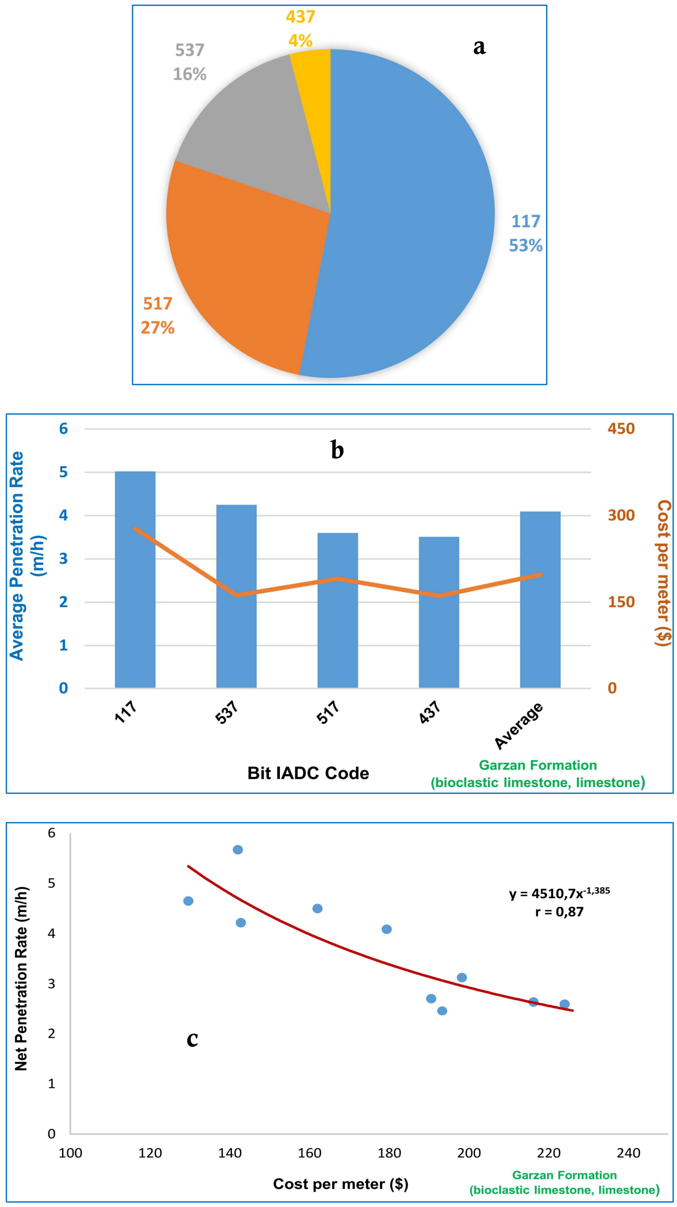

Fig. 16. Tricone rock bit types, rates of penetration and costs of meter used in the Garzan Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

In the literature, many penetrations rate models and drilling cost studies are encountered. The most important ones can be regarded as follows: Galle and Woods (1963), Young (1969), Lummus (1970), Reed (1972), Mechem and Fullerton (1973), Bourgoyne and Young (1974), Chenevert and Hollo (1981), Warren (1987), Wojtanowicz and Kuru (1993), Barragan and Santos (1997), Ozbayoğlu and Omurlu (2005), Hapnes (2014), Erdoğan et al. (2018), Okumus and Sakcali (2019), Kor and Altun (2020a; 2020b), Hazbeh et al. (2021) Kor et al. (2020) and Ozdemir et al. (2021b). Conditions in which the drilling cost is minimized are possible by optimizing the drilling parameters. For such a procedure, the drilling cost is examined according to parameters of the weight on bit and the rotation speed of drill string (Fig. 3).

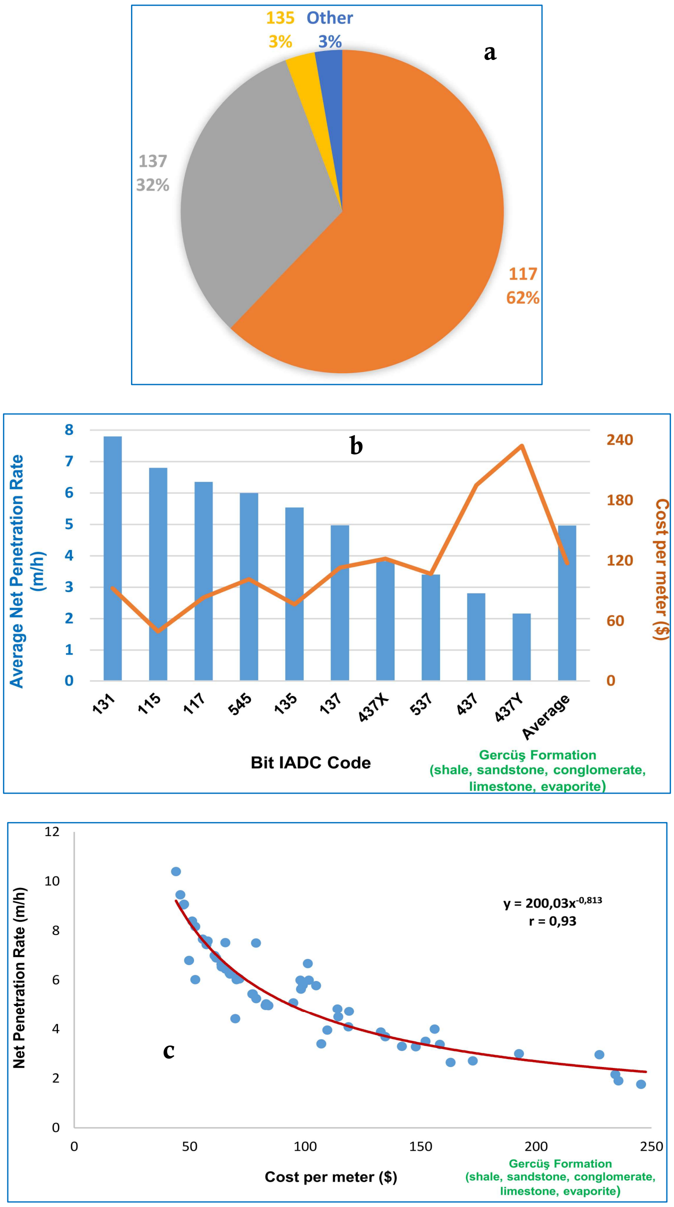

Fig. 17. Tricone rock bit types, rates of penetration and costs of meter used in the Gercüş formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter.

In Figs. 6 and 7, weights on bit and rotation speeds applied to in the formations the Southeast Anatolian and Thrace basins are seen. The weights on bit are 5-12 tons and the rotation speed are 98-148 (rpm). There is a negative high correlation (r = 0.87) between weights on bit and rates of penetration in well drilling in the oil and gas production basins of Turkey (Fig. 8). The reason for this high negative correlation is that the drill bit is embeded in the formation during drilling due to excessive weight on bit. Because the bit teeth are embeded in the formation due to excessive weight, effective cutting-fracturing operation cannot take place. Therefore, the rates of penetration decrease. The explanation for this is that increasing the weight on bit does not necessarily mean that the rate of penetration will increase. As a matter of fact, as the weights on bit were increased in both basins, there were decreases the rates of penetration.

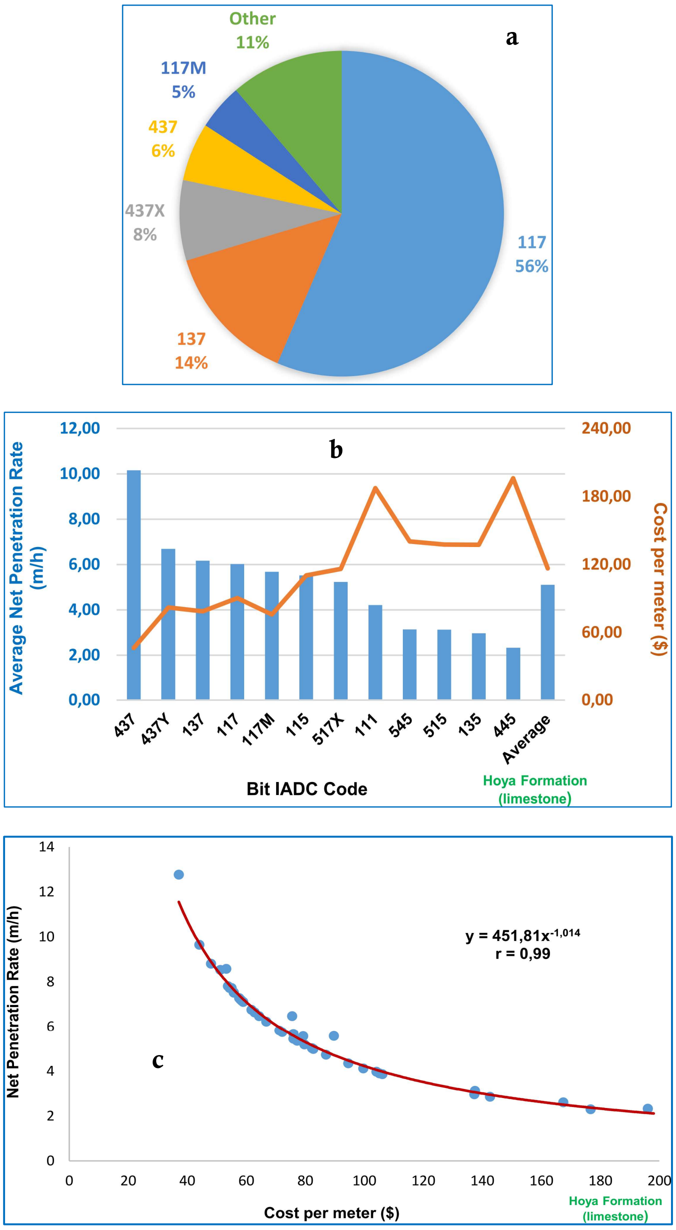

Fig. 18. Tricone rock bit types, rates of penetration and costs of meter used in the Hoya formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

Therefore, the weights on bit should be reduced in both basin formations. In the formations of the Southeastern Anatolian and Thrace basins, rates of penetration of 2.38-7.73 meters/hour can be achieved with tricone rock bits (Fig. 9). The average rate of penetration is 4.31 m/h. The cost per meter ranges from 94.04 US $ to 414.42 US $. The average meter cost is 196.59 US $ (Fig. 10). There is a naturally negative relationship between progress rates and costs (Figs. 11 and 12). In other words, costs per meter decrease as the rates of penetration increase (Fig. 12).

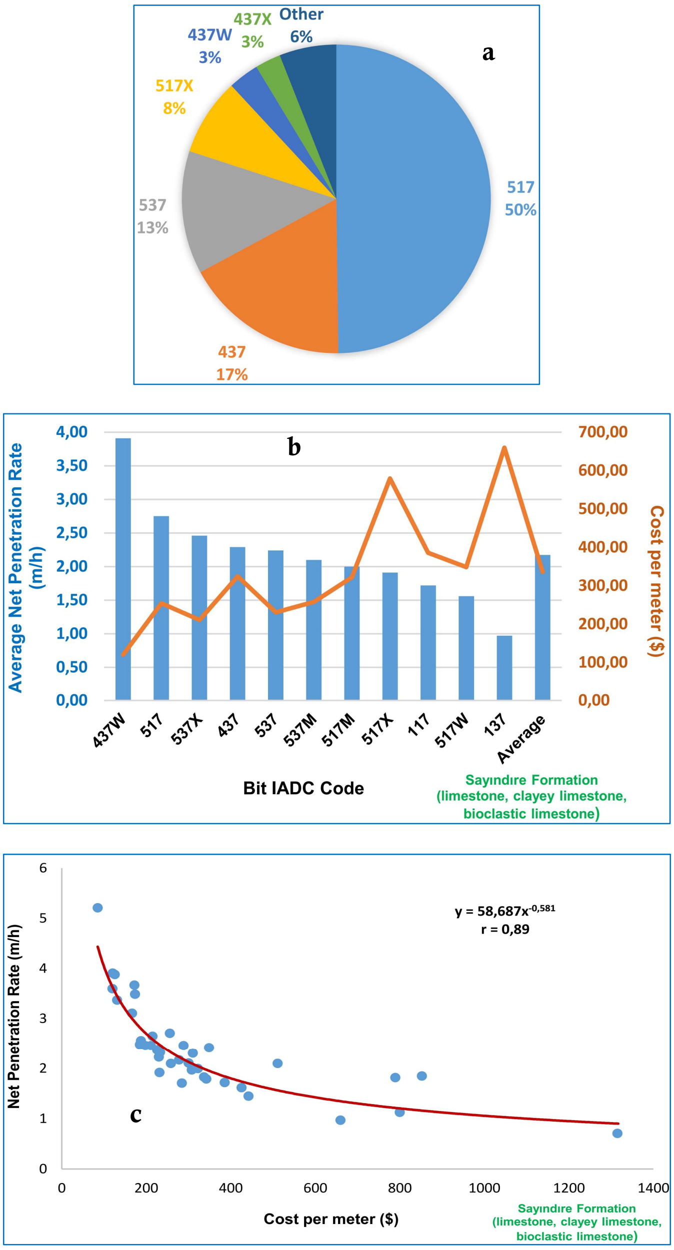

Fig. 19. Tricone rock bit types, rates of penetration and costs of meter used in the Sayındere Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1. Rate of penetration and cost assessment according to formations

3.1.1. Lower Germav Formation of the Southeastern Anatolia Basin

In the Lower Germav Formation, the most widely used bit with a ratio of 51% is IADC code 437-bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) (Fig. 13). With this bit type, the average penetration rate per hour in the Lower Germav Formation is 5.15 m. The average net penetration rate per hour for all bit types was found to be 3.20 m. In the Lower Germav Formation, the net penetration rate is 1.69-5.55 m, cost per meter is 90.45-305.95 $.

3.1.2. Upper Germav Formation of the Southeastern Anatolia Basin

In the Upper Germav Formation, the most commonly used bit with a ratio of 53% is IADC code 137-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 14). With this bit type, the average penetration rate per hour in the Upper Germav Formation is 6.32 m. The average net penetration rate per hour for all bit types was found to be 4.60 m. In the Upper Germav Formation, the net penetration rate is 1.91-10.80 m, the cost per meter is 31.39-245.47 US $.

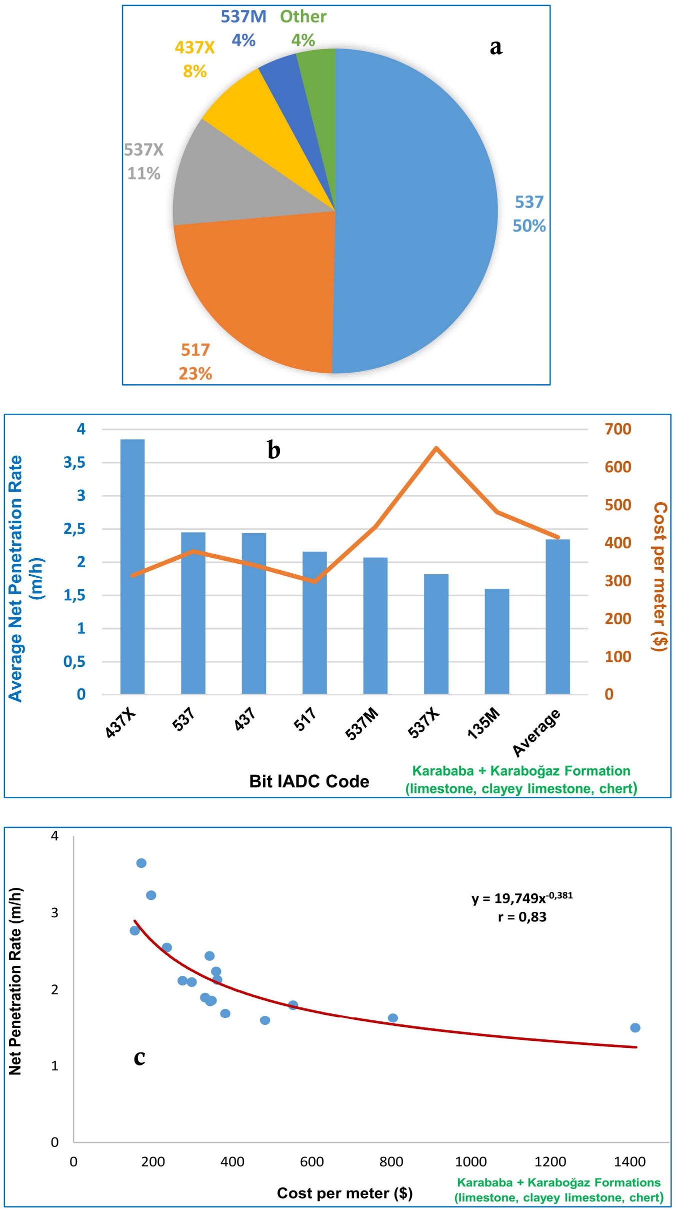

Fig. 20. Tricone rock bit types, rates of penetration and costs of meter used in the Karababa and Karaboğaz Formations; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.3. Germav Formation of the Southeastern Anatolia Basin

In the Germav Formation, the most widely used bit with a ratio of 25% is IADC code 437X bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts) (Fig. 15). With this bit type, the average penetration rate per hour in the Germav Formation is 3.72 m. The average net penetration rate per hour for all bit types was found to be 4.00 m. In the Germav Formation, the net penetration rate is 2.06-14.00 m, cost per meter is 41.06-263.54 $.

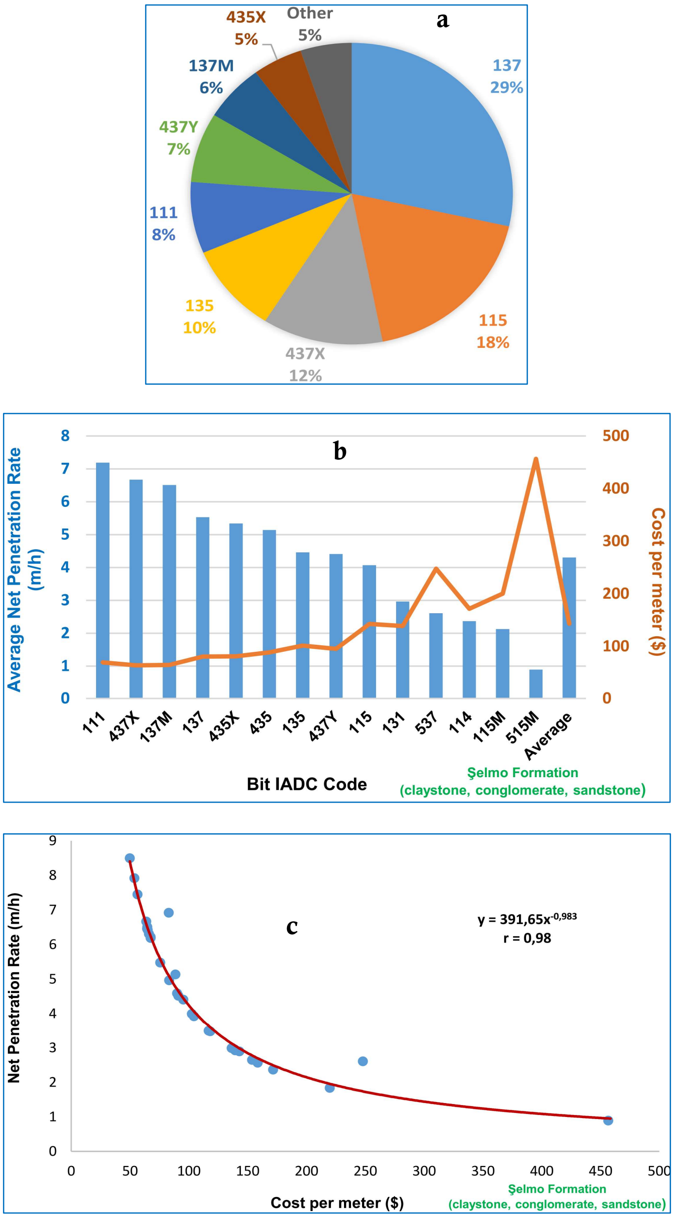

Fig. 21. Tricone rock bit types, rates of penetration and costs of meter used in the Şelmo Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.4. Garzan Formation of the Southeastern Anatolia Basin

In the Garzan Formation, the most commonly used bit with a ratio of 53% is IADC code 137-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 16). With this bit type, the average penetration rate per hour in the Garzan Formation is 5.02 m. The average net penetration rate per hour for all bit types was found to be 4.10 m. In the Garzan Formation, the net penetration rate is 2.46-5.67 m, cost per meter is 129.60-224.00 $.

3.1.5. Gercüş Formation of the Southeastern Anatolia Basin

In the Gercüş Formation, the most widely used bit with a ratio of 62% is IADC code 117-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 17). With this bit type, the average penetration rate per hour in the Gercüş Formation is 6.35 m. The average net penetration rate per hour for all bit types was found to be 4.97 m. In the Gercüş Formation, the net penetration rate is 1.76-10.40 m, the cost per meter is 44.09-245.52 US $.

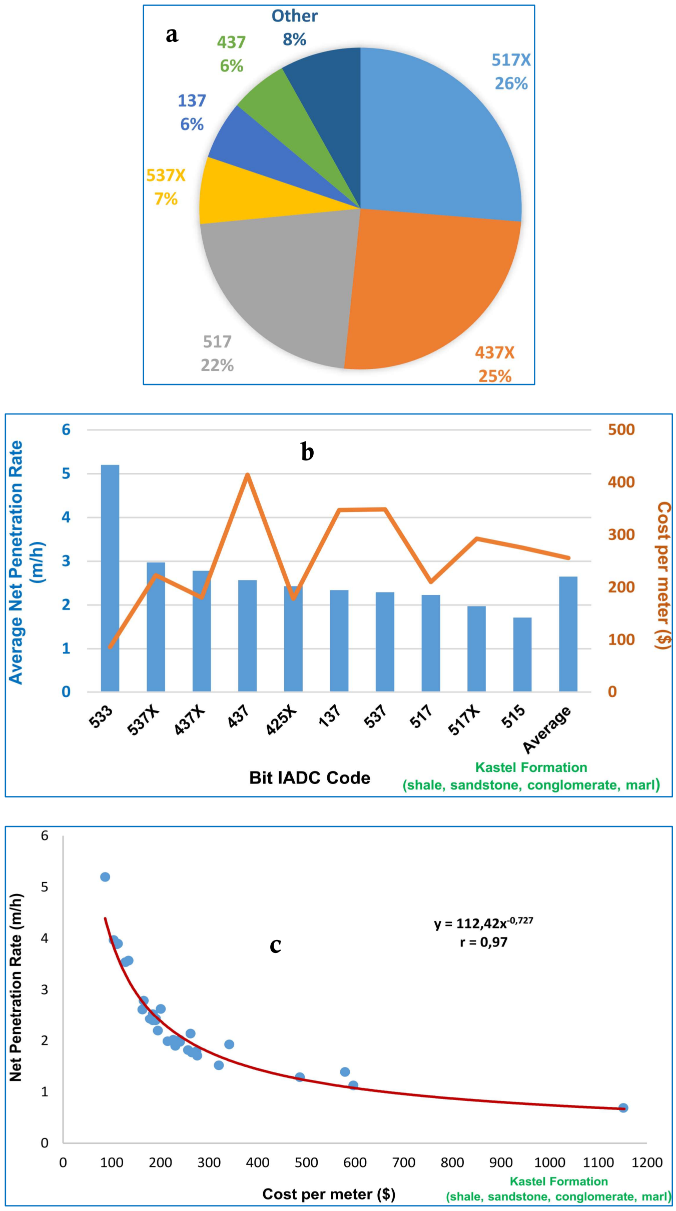

Fig. 22. Tricone rock bit types, rates of penetration and costs of meter used in the Kastel Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.6. Hoya Formation of the Southeastern Anatolia Basin

In the Hoya Formation, the most commonly used bit with a ratio of 56% is IADC code 117-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 18). With this bit type, the average penetration rate per hour in the Hoya

Formation is 6.02 m. The average net penetration rate per hour for all bit types was found to be 5.10 m. In the Hoya Formation, the net penetration rate is 2.33-2.77 m, cost per meter is 37.13-196.10 $.

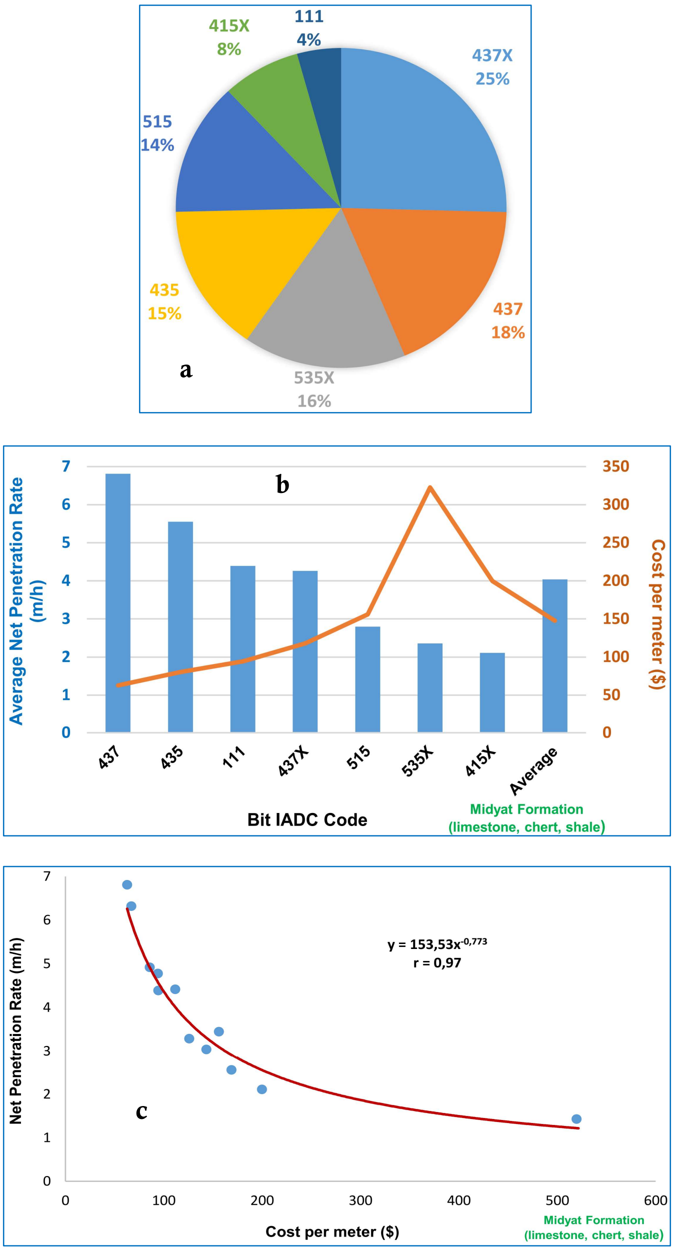

Fig. 23. Tricone rock bit types, rates of penetration and costs of meter used in the Midyat Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.7. Sayındere Formation of the Southeastern Anatolia Basin

In the Sayındere Formation, the most widely used bit with a ratio of 50% is IADC code 517-bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) (Fig. 19). With this bit type, the average penetration rate per hour in the Sayındere Formation is 2.75 m. The average net penetration rate per hour for all bit types was found to be 2.17 m. In the Sayındere Formation, the net penetration rate is 0.71-5.21 m, cost per meter is 85.00-1314.89 $.

3.1.8. Karababa and Karaboğaz Formations of the Southeastern Anatolia Basin

In the Karababa and Karaboğaz Formations, the most commonly used bit with a ratio of 50% is IADC code 537-bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) (Fig. 20). With this bit type, the average penetration rate per hour in the Karababa and Karaboğaz Formations is 2.45 m. The average net penetration rate per hour for all bit types was found to be 2.34 m. In the Karababa and Karaboğaz Formations, the net penetration rate is 1.50-3.65 m, the cost per meter is 170.94 -1414.23 US $.

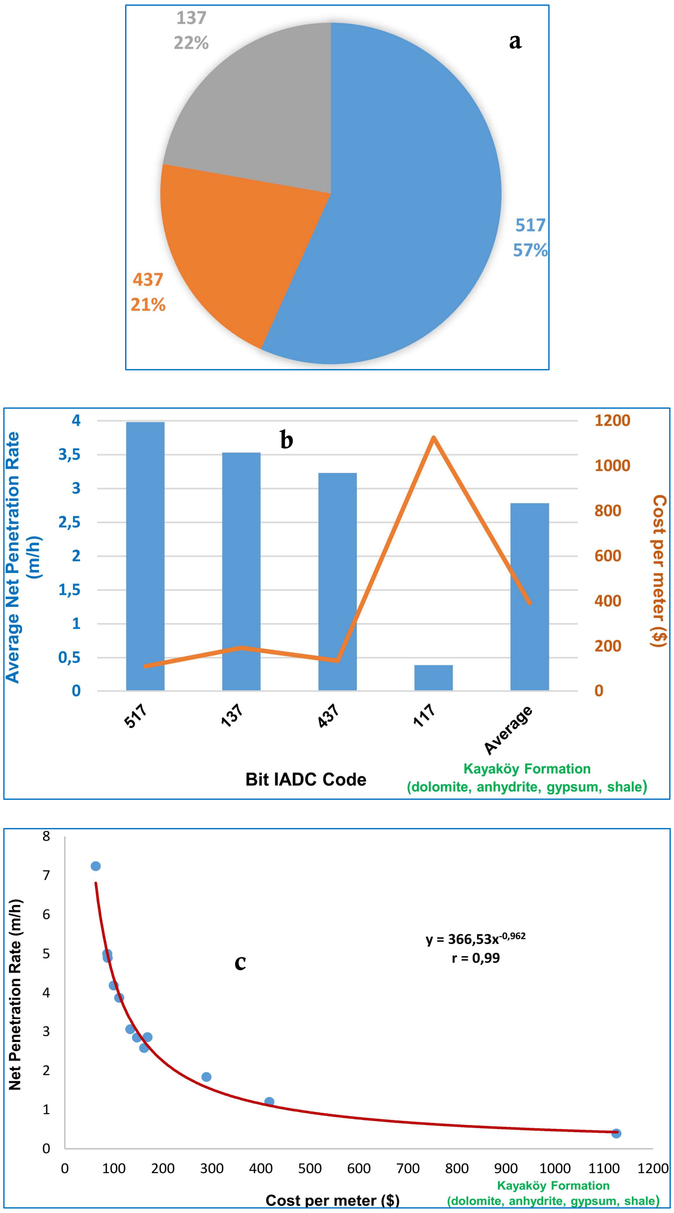

Fig. 24. Tricone rock bit types, rates of penetration and costs of meter used in the Kayaköy Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.9. Şelmo Formation of the Southeastern Anatolia Basin

In the Şelmo Formation, the most widely used bit with a ratio of 29% is IADC code 137-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 21). With this bit type, the average penetration rate per hour in the Şelmo Formation is 5.53 m. The average net penetration rate per hour for all bit types was found to be 4.31 m. In the Şelmo Formation, the net penetration rate is 0.89-8.50 m, the cost per meter is 49.89-456.51 US $.

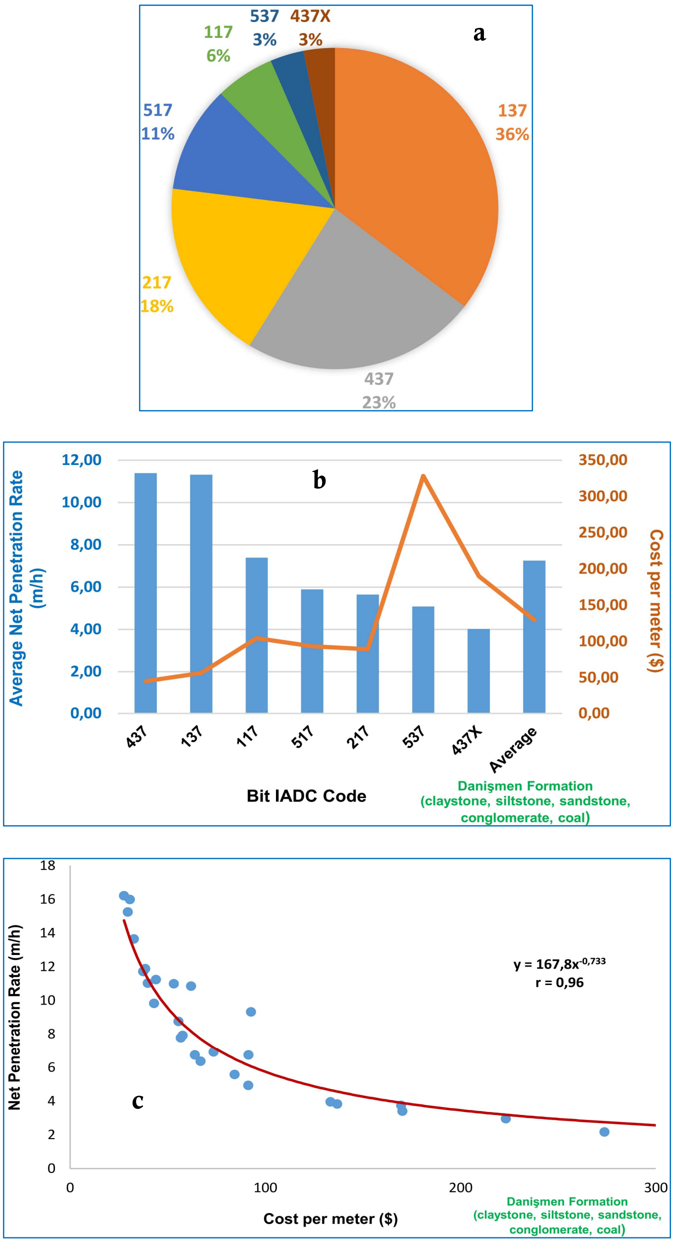

Fig. 25. Tricone rock bit types, rates of penetration and costs of meter used in the Danişmen Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.10. Kastel Formation of the Southeastern Anatolia Basin

In the Kastel Formation, the most widely used bit with a ratio of 26% is IADC code 517X bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts) (Fig. 22). With this bit type, the average penetration rate per hour in the Kastel Formation is 1.97 m. The average net penetration rate per hour for all bit types was found to be 2.65 m. In the Kastel formation, the net penetration rate is 0.69-5.20 m, the cost per meter is 86.49-1151.42 US $.

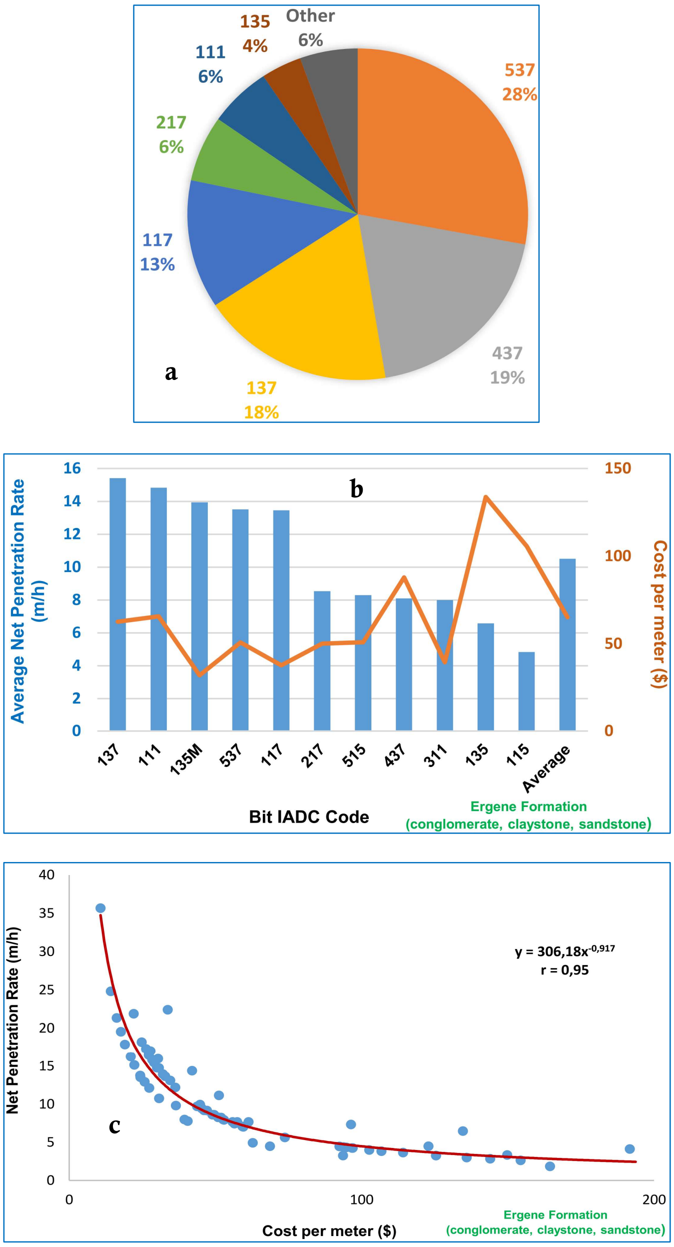

Fig. 26. Tricone rock bit types, rates of penetration and costs of meter used in the Ergene Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.11. Midyat Formation of the Southeastern Anatolia Basin

In the Midyat Formation, the most commonly used bit with a ratio of 25% is IADC code 437X bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts) (Fig. 23). With this bit type, the average penetration rate per hour in the Midyat Formation is 4.26 m. The average net penetration rate per hour for all bit types was found to be 4.04 m. In the Midyat Formation, the net penetration rate is 1.43-6.81 m, the cost per meter is 62.72-519.56 US $.

3.1.12. Kayaköy Formation of the Southeastern Anatolia Basin

In the Kayaköy Formation, the most widely used bit with a ratio of 57% is IADC code 517-bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) (Fig. 24). With this bit type, the average penetration rate per hour in the Kayaköy Formation is 3.98 m. The average net penetration rate per hour for all bit types was found to be 2.78 m. In the Kayaköy Formation, the net penetration rate is 0.39-7.24 m, the cost per meter is 63.09-1125.39 US $.

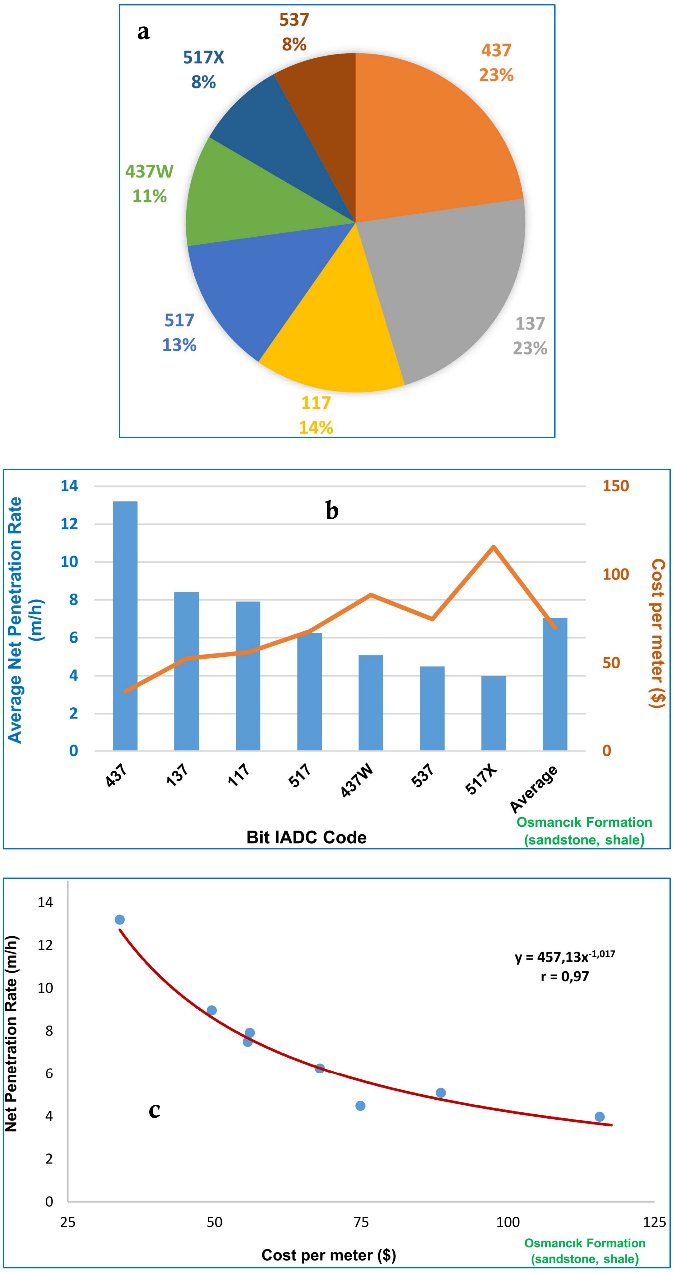

Fig. 27. Tricone rock bit types, rates of penetration and costs of meter used in the Osmancık Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.13. Danişmen Formation of the Thrace Basin

In the Danişmen Formation, the most commonly used bit with a ratio of 36% is IADC code 137-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 25). With this bit type, the average penetration rate per hour in the Danişmen Formation is 11.32 m. The average net penetration rate per hour for all bit types was found to be 7.25 m. In the Danişmen Formation, the net penetration rate is 2.00-16.22 m, the cost per meter is 27.62-771.64 US $.

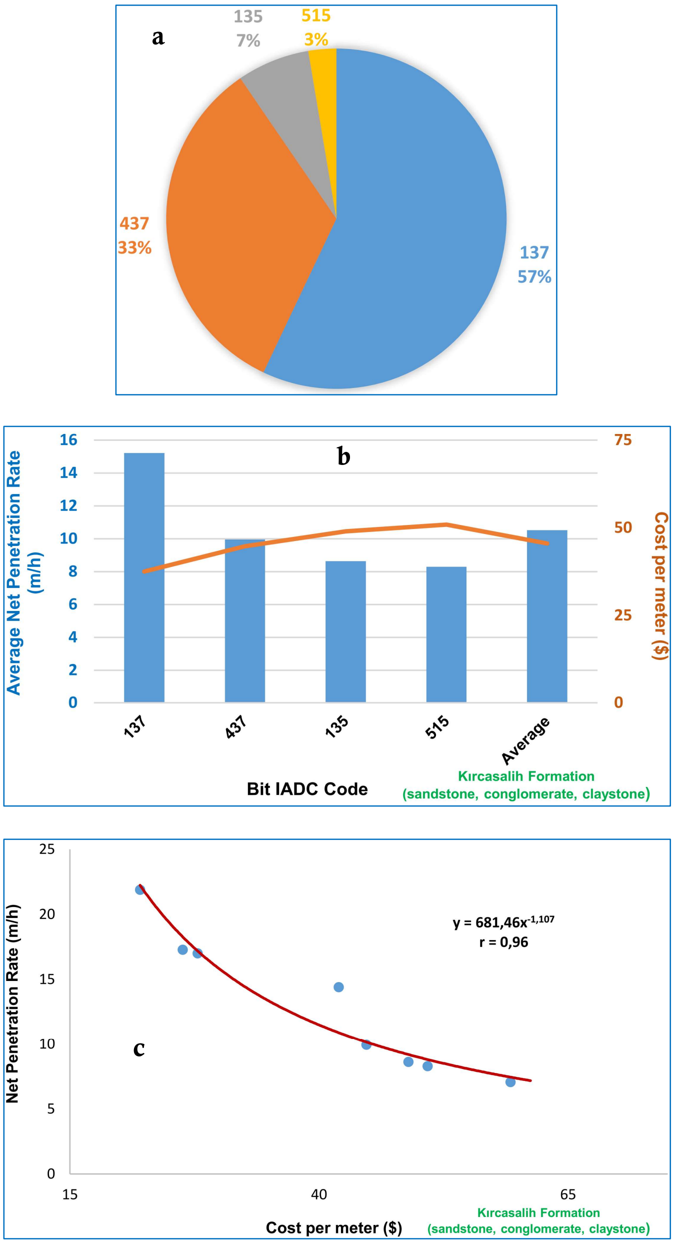

Fig. 28. Tricone rock bit types, rates of penetration and costs of meter used in the Kırcasalih Formation; a) percentage distribution of tricone bits commonly used in the formation according to IADC codes, b) relationship between average net penetration rates and bit IADC codes, c) relationship between net penetration rates and costs of meter

3.1.14. Ergene Formation of the Thrace Basin

In the Ergene Formation, the most widely used bit with a ratio of 28% is IADC code 537-bit (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) (Fig. 26). With this bit type, the average penetration rate per hour in the Ergene Formation is 13.52 m. The average net penetration rate per hour for all bit types was found to be

10.50 m. In the Ergene Formation, the net penetration rate is 1.85-35.67 m, the cost per meter is 10.72-164.47 US $.

3.1.15. Osmancık Formation of the Thrace Basin

In the Osmancık Formation, the most commonly used bits with a ratio of 23% is IADC code 437 (tungsten carbide (insert) tooth, sealed friction bearing with gauge protection) and with a ratio of 23% is IADC code 137 (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 27). While the net penetration rate per hour is 13.22 in Osmancık Formation with the IADC code 437-bit, 8.42 m is for the IADC code 137 bit. The average net penetration rate per hour for all bit types was found to be 7.05 m. In this formation, the net penetration rate is 3.98-13.20 m, cost per meter is 33.85-115.65 US $.

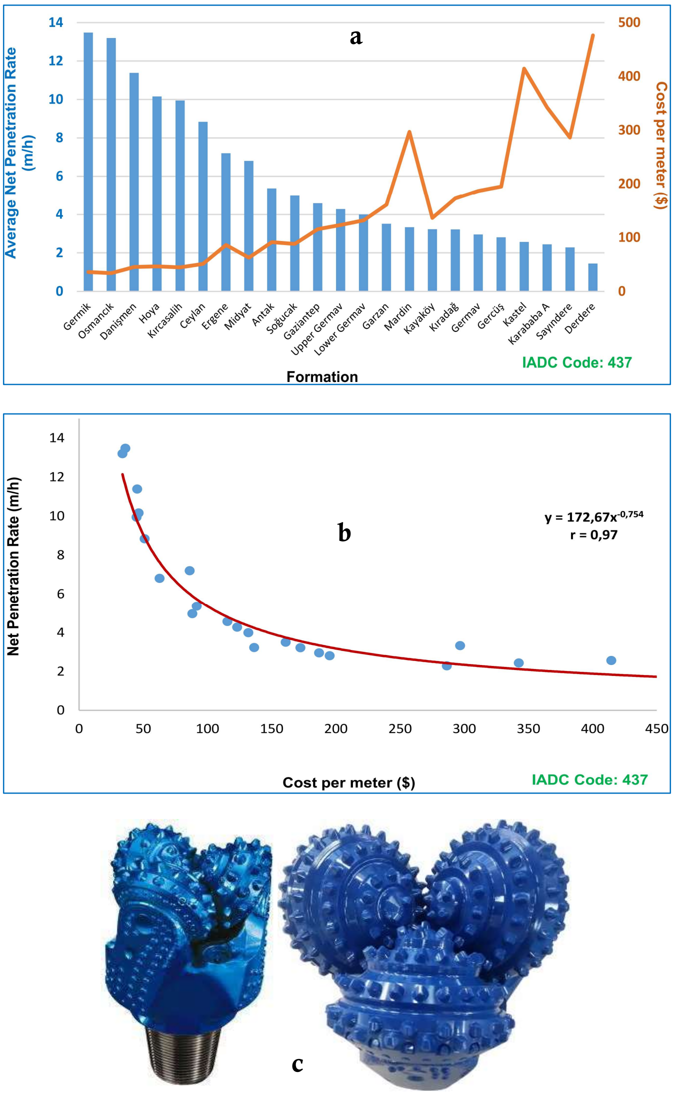

Fig. 29. Rates of penetration and costs of meter for IADC 437 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 437 tricone rock bit

3.1.16. Kırcasalih Formation of the Thrace Basin

In the Kırcasalih Formation, the most widely used bit with a ratio of 57% is IADC code 137-bit (steel (milled) tooth, sealed friction bearing with gauge protection) (Fig. 28). With this bit type, the average penetration rate per hour in the Kırcasalih Formation is 15.22 m. The average net penetration rate per hour for all bit types was found to be 10.52 m. In the Kırcasalih Formation, the net penetration rate is 7.07-21.89 m, the cost per meter is 22.04-59.23 US $.

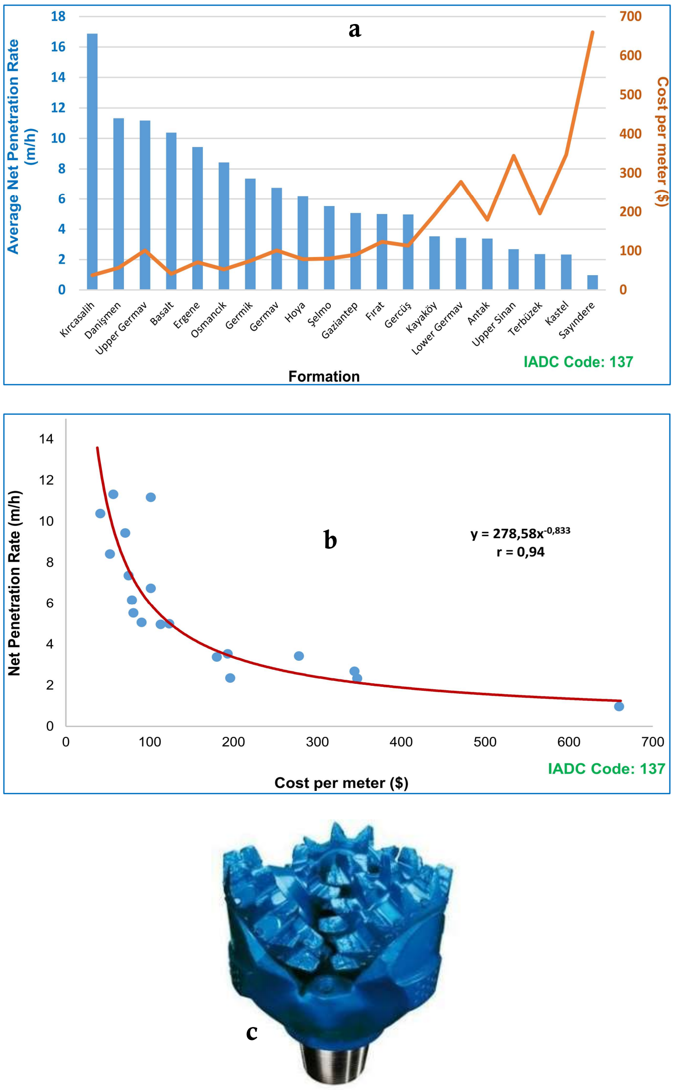

Fig. 30. Rates of penetration and costs of meter for IADC 137 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 137 tricone bit

3.2. Penetration rate and cost assessment according to IADC codes

3.2.1. IADC code 437 bit

These bits are designed for drilling in soft formations with low compressive strength. The teeth normally have a small tip diameter and are short. The teeth are also spaced widely and unevenly. The cones have a large offset. These bits have tungsten carbide (insert) tooth, sealed friction bearing with gauge protection (Fig. 29).

With this bit type, in the Southeastern Anatolia and Thrace basins, the highest average ROP was obtained in the Germik Formation with 13.48 m/h, and the lowest average ROP was obtained in the Derdere Formation with 1.45 m/h. The cost per meter is 36.01-476.28 US $.

3.2.3. IADC code 117 bit

These bits are designed for drilling in very soft formations with low compressive strength. They have the tallest and widest tooth. The wide tooth spacing and a large offset allow a higher ROP. The gage faces and the inner teeth back faces are hardfaced (Fig. 31). With this bit type, in the Southeastern Anatolia and Thrace basins, the highest average ROP was obtained in the Ergene Formation with 13.45 m/h, and the lowest average ROP was obtained in the Sayındere Formation with 1.72 m/h. The cost per meter is 37.72-385.70 US $.

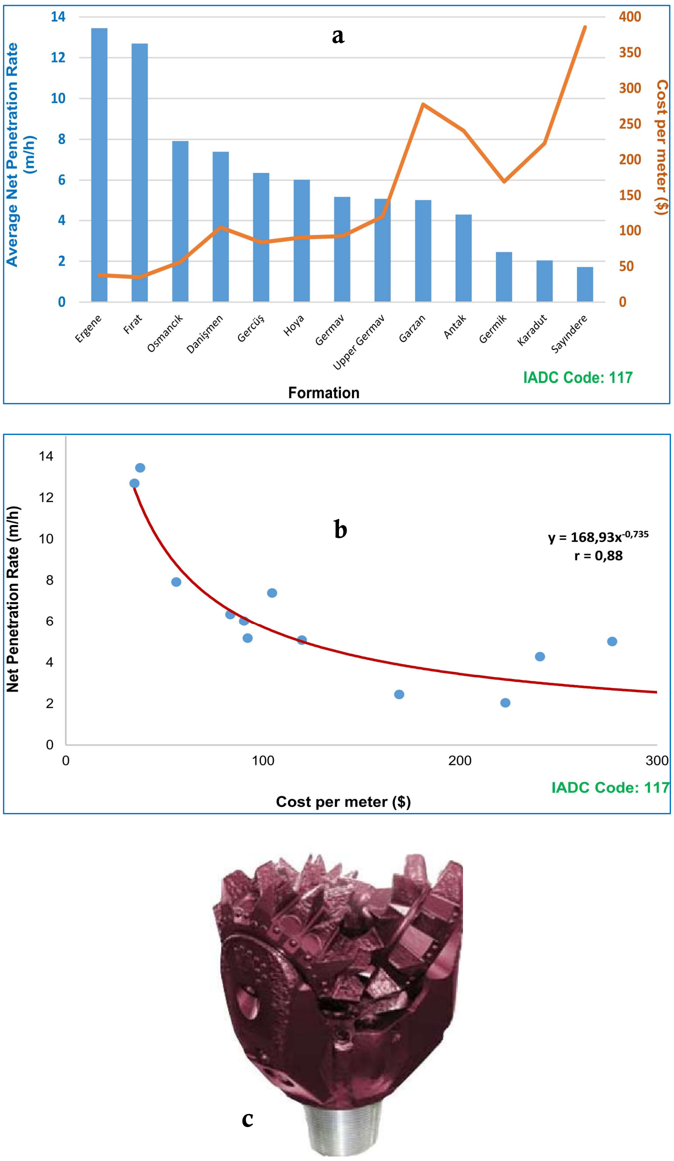

Fig. 31. Rates of penetration and costs of meter for IADC 117 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins. a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 117 tricone bit

3.2.4. IADC code 517 bit

These bits are designed for drilling in soft to medium formations with low compressive strength. The main teeth normally have a small tip diameter and are short. The teeth are spaced unevenly and the cones have a large offset (Fig. 32). With this bit type, in the Southeastern Anatolia and Thrace Basins, the highest average ROP was obtained in the Germik Formation with 9.93 m/h, and the lowest average ROP was obtained in the Karaboğaz Formation with 1.88 m/h. The cost per meter is 50.27-342.41 US $.

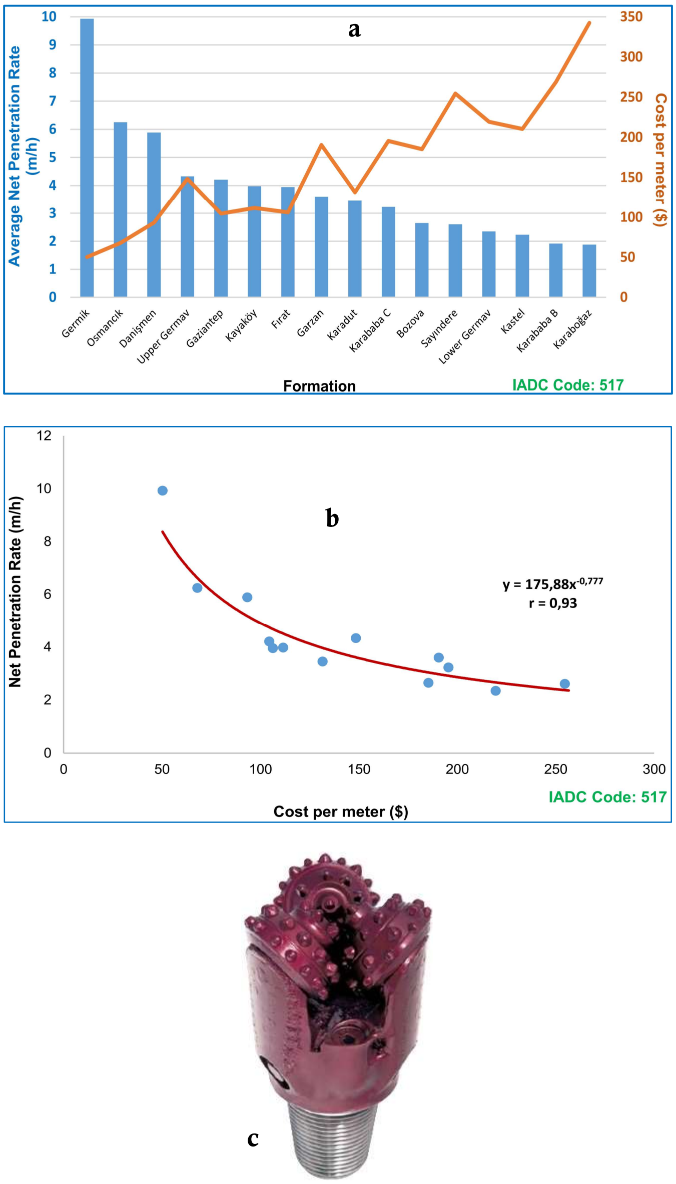

Fig. 32. Rates of penetration and costs of meter for IADC 517 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 517 tricone bit

3.2.5. IADC code 537 bit

These bits are generally designed for drilling in medium formations with low compressive strength, but it also performs well in semi-abrasive formations. The main teeth normally have a small tip diameter and are short, but in order to avoid tip damaged during drilling, teeth high are set low. The teeth are spaced unevenly and the cones have a moderate degree of offset (Fig. 33). With this bit type, in the Southeastern Anatolia and Thrace Basins, the highest average ROP was obtained in the Ergene Formation with 13.52 m/h, and the lowest average ROP was obtained in the Mardin Formation with 1.85 m/h. The cost per meter is 50.83-419.81 $.

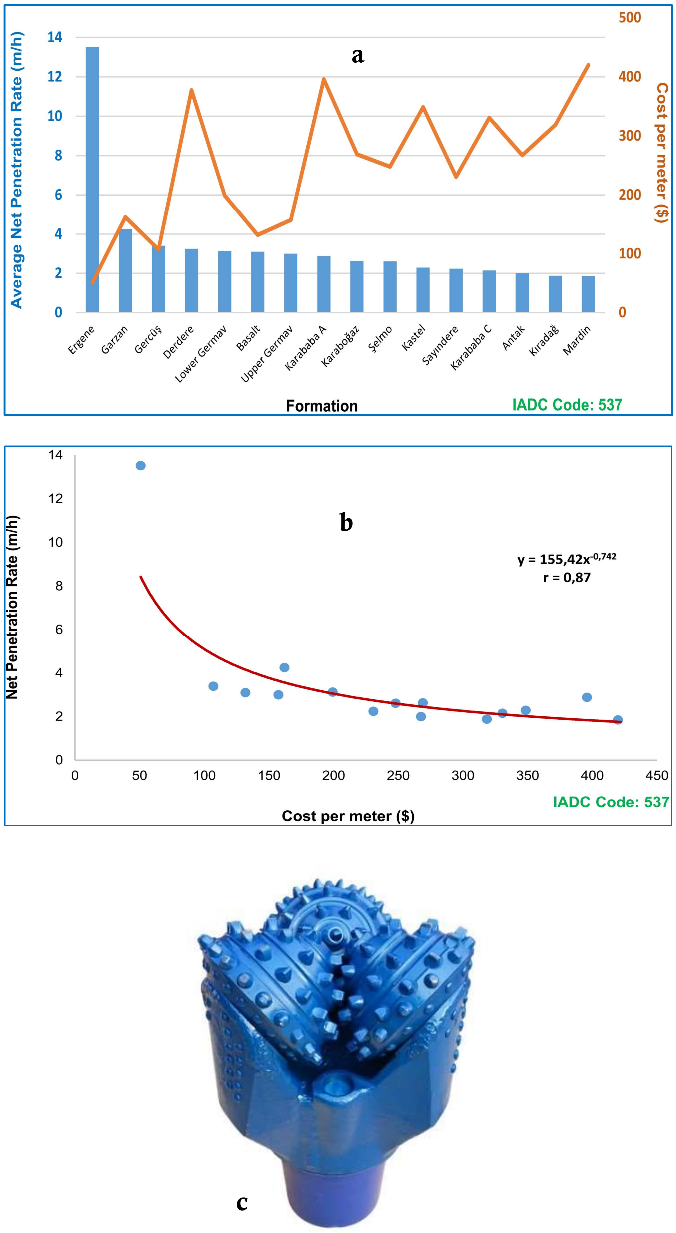

Fig. 33. Rates of penetration and costs of meter for IADC 537 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 537 tricone bit

3.2.6. IADC code 437X bit

These bits are designed for drilling in soft formations with low compressive strength. The teeth normally have a small tip diameter and are short. The teeth are also spaced widely and unevenly. The cones have a large offset. These bits have tungsten carbide (insert) tooth, sealed friction bearing with gauge protection, predominantly chisel tooth inserts (Fig. 34). With this bit type, in the Southeastern Anatolia and Thrace Basins, the highest average ROP was obtained in the Hoya Formation with 8.05 m/h, and the lowest average ROP was obtained in the Karadut Formation with 1.80 m/h. The cost per meter is 53.62-254.98 US $.

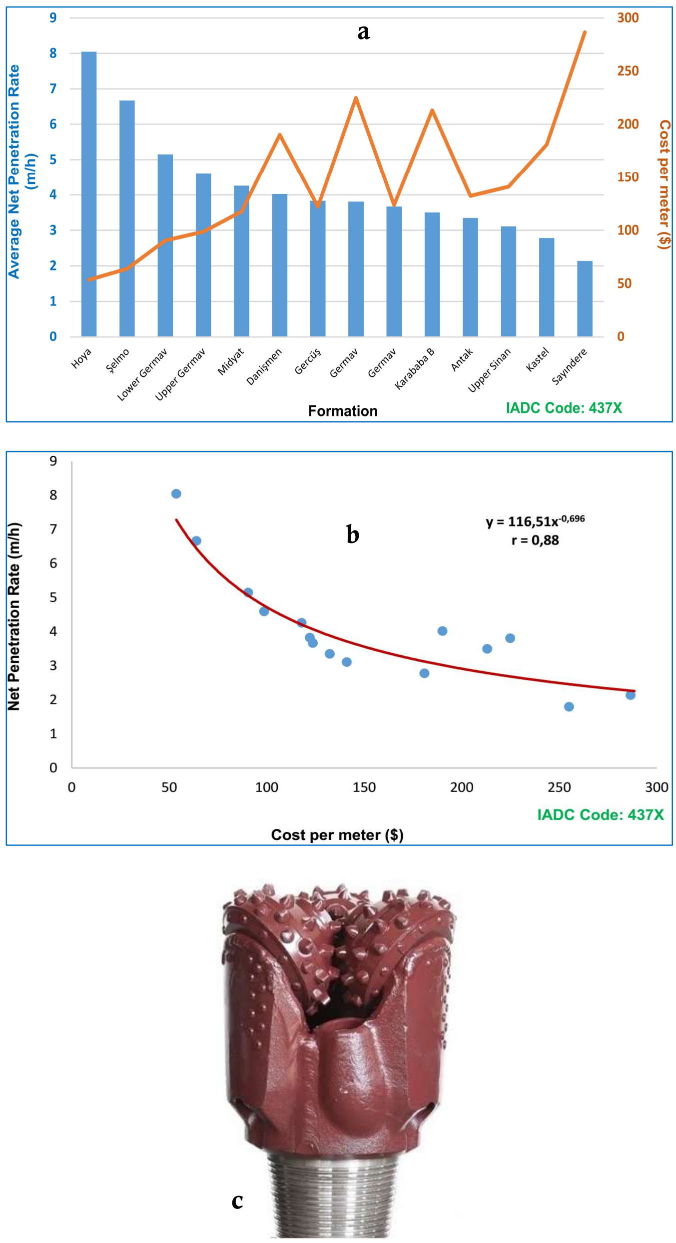

Fig. 34. Rates of penetration and costs of meter for IADC 437X tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 437X tricone bit.

3.2.7. IADC code 111 bit

These bits are designed for drilling in very soft formations with low compressive strength. They have the tallest and widest tooth. The wide tooth spacing and a large offset allow a higher ROP (rate of penetration). The gage faces and the inner teeth back faces are hardfaced (Fig. 35). With this bit type, in the Southeastern Anatolia and Thrace Basins, the highest average ROP was obtained in the Ergene Formation with 14.83 m/h, and the lowest average ROP was obtained in the Hoya Formation with 4.21 m/h. The cost per meter is 14.24-187.42 US $.

3.3. Performance and cost assessment based on diameter of tricone rock bit and basins

Ozdemir et al. (2021b), the drilling times and penetration rates of the wells drilled in the oil and gas production basins of Turkey and the drillability of formations have been examined. Ozdemir et al. (2021a) have assessed the drilling engineering characteristics and costs of wells drilled in oil and gas production basins of Turkey. In the aforementioned research, it is seen that wells that usually start with a diameter of 20 or 16 inches are continued with a diameter of 12 ¼" and ended with a diameter of 8 5/8 (Fig. 36).

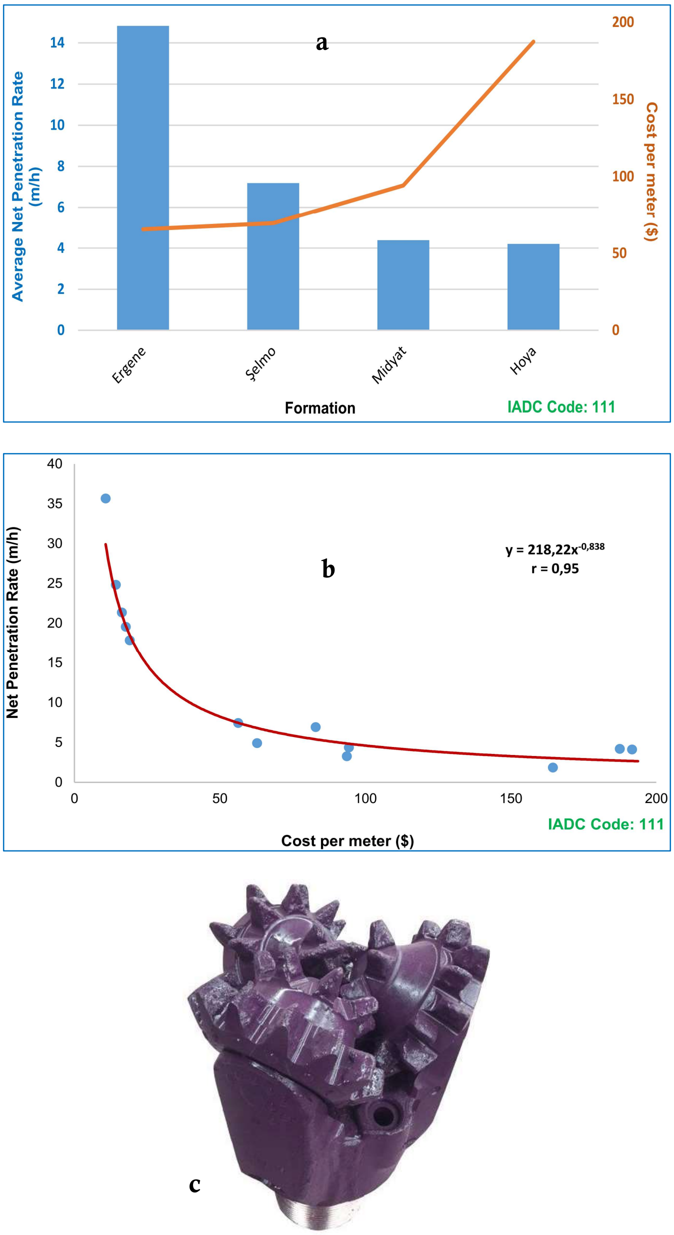

Fig. 35. Rates of penetration and costs of meter for IADC 111 tricone bits used in the formations in Southeastern Anatolia and Thrace Basins; a) relationship between average net penetration rates and formations, b) relationship between net penetration rates and costs of meter, c) view of an IADC 111 tricone bit

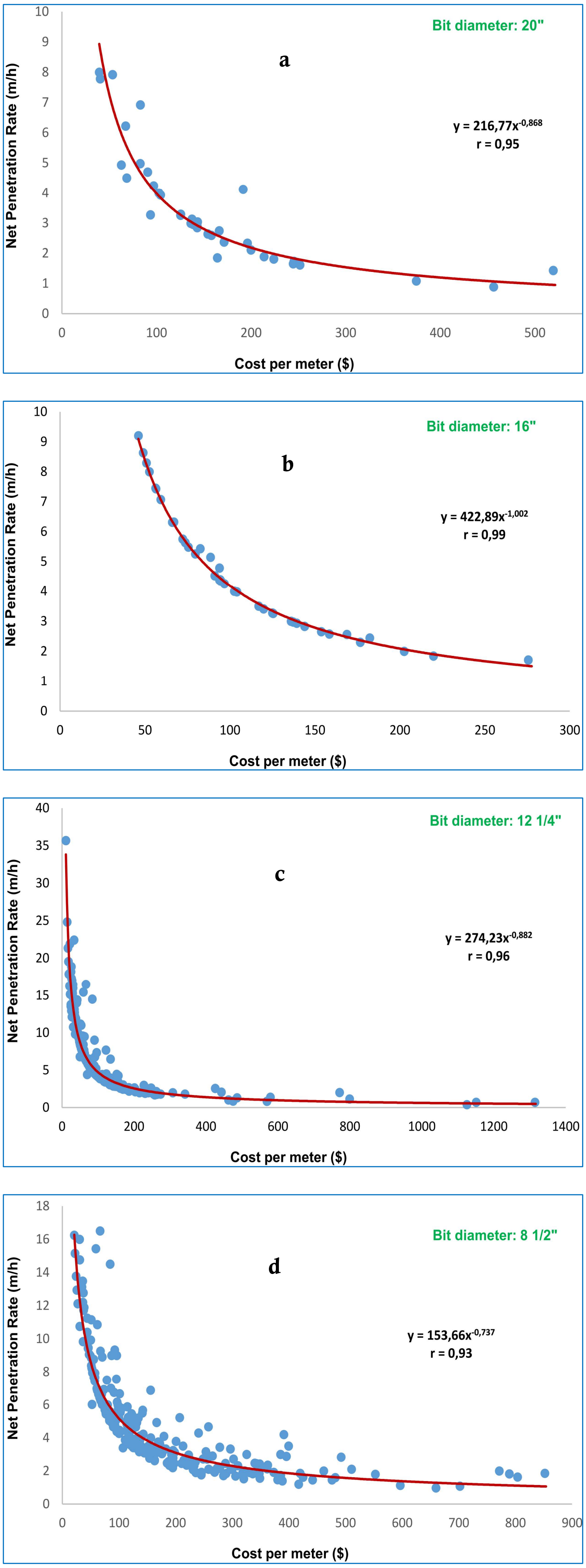

Fig. 36. Relationships between net penetration rate and cost per meter according to diameters of tricone bits; a) bit diameter: 20", b) bit diameter: 16", c) bit diameter: 12 1/4", d) bit diameter: 8 1/2"

For the 20 inches tricone rock bits, rates of penetration are in the range of 0.89-10.38 m, and costs are 39.47 US $-519.56 US $. For the 16 inches tricone rock bits, rates of penetration are in the range of 1.71-9.20 m, and costs are 46.10 US $-275.64 US $. For the 12 ¼ inches tricone rock bits, rates of penetration are in the range of 0.39 to 35.67 m, and costs are 10.72 US $ to 1314.89 US $. For the 8 1/2 inches tricone rock bits, rates of penetration are in the range of 0.97-16.50 m, and costs are 21.07 US $-852.08 US $.

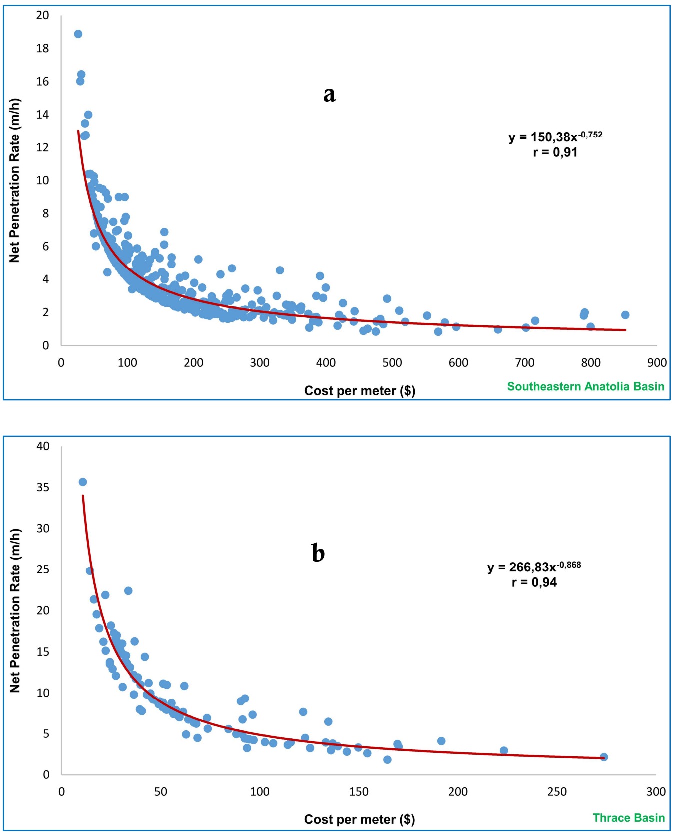

Fig. 37. Relationship between net penetration rates and costs per meter; a) Southeastern Anatolia Basin and b) Thrace Basin

In the Southeastern Anatolia basin, rates of penetration are in the range of 0.84-18.87 m, and costs are 25.87 US $-852.08 US $ (Fig. 36). In the Thrace Basin, rates of penetration are in the range of 1.85-35.67 m and costs are 10.72 US $-273.67 US $ (Fig. 37).

4. Conclusions

In this study, a new global chart is presented to be used for the selection of tricone rock bits suitable for the formation to be drilled, according to the IADC codes. According to the rock bit types used, it is inferred that the formations in Turkey's oil and gas fields are predominantly formed of formations which easily and normally drillable. Accordingly, the commonly preferred milled-tooth tricone bits in easily drillable formations are 117 and 111 IADC coded bits. In hardly drillable formations, it is observed that generally milled-tooth bits are not preferred. The commonly preferred insert-tooth bits for easily drillable formations are 437 and 437X IADC coded bits. The commonly preferred insert-tooth bits in normally drillable formations are 517 and 537 and 517X IADC coded bits. There is a negative high correlation between weights on bit and rates of penetration in well drilling in the oil and gas production basins of Turkey. Hence, the weights on bit should be reduced in both basin formations. In the formations of the Southeastern Anatolian and Thrace Basins, rates of penetration of 2.38-7.73 meters/hour can be achieved with tricone rock bits. The average rate of penetration is 4.31 m/h. The cost per meter ranges from 94.04 to 414.42 US $. The average meter cost is 196.59 US $. There is a naturally negative relationship between progress rates and costs. In other words, costs per meter decrease as the rates of penetration increase.

In Southeastern Anatolia and Thrace Basins are seen that wells that usually start with a diameter of 20 or 16 inches are continued with a diameter of 12 ¼" and ended with a diameter of 8 5/8. For the 20 inches tricone rock bits, rates of penetration are in the range of 0.89-10.38 m, and costs are 39.47 US $-519.56 US $. For the 16 inches tricone rock bits, rates of penetration are in the range of 1.71-9.20 m, and costs are 46.10 US $-275.64 US $. For the 12 ¼ inches tricone rock bits, rates of penetration are in the range of 0.39 to 35.67 m, and costs are 10.72 US $ to 1314.89 US $. For the 8 1/2 inches tricone rock bits, rates of penetration are in the range of 0.97-16.50 m, and costs are 21.07 US $-852.08 US $. In the Southeastern Anatolia Basin, rates of penetration are in the range of 0.84-18.87 m, and costs are 25.87 US $-852.08 US $. In the Thrace basin, rates of penetration are in the range of 1.85 - 35.67 m, and costs are 10.72 US $-273.67 US $. PDC bits have been widely used in recent years. Therefore, a study similar to this study can be performed with PDC bits for Southeastern Anatolia and Thrace Basins. For the same formations, the results of study can be compared.

Appendix 1. IADC codes of tricone bits used in other formations in the Southeast Anatolian Basin

Formation	IADC Codes of Tricone Bits
Areban Formation (sandstone)	437, 517, 537
Antak Formation (shale, conglomerate, sandstone)	137, 437, 517
Bakük Formation (limestone, sandstone)	537, 617, 637
Basalts	515, 517
Basement (limestone)	437, 517
Becirman Formation (claystone, sandstone)	137, 517
Bedinan Formation (sandstone, shale)	517, 537
Beloka Formation (limestone, bioclastic limestone)	517, 537
Besni Formation (limestone)	137, 437, 517
Bozova Formation (limestone)	437, 517, 537
Bulkasım Formation (shale)	137, 437
Çamurlu Formation (conglomerate, sandstone)	537

Dadaş Formation (shale)	437, 517
Derdere Formation (limestone, dolomite)	517, 537
Dinçeri Formation (claystone)	537
Elmakaya Formation (sandstone, conglomerate)	114, 117
Fırat Formation (limestone, bioclastic limestone)	135, 137, 515, 517
Germik Formation (conglomerate, claystone, limestone, gypsum)	115, 137, 435, 517
Güllüce Formation (marble)	137, 437, 537
Hazro Formation (shale, limestone)	517, 537
Karadut Formation (shale, limestone, conglomerate)	137, 437, 517
Karakurt Volcanics (basalt, tuff)	137, 437, 537
Kelereş Formation (shale, marl, sandstone)	437, 517
Kıradağ Formation (shale, sandstone)	437, 517, 537
Koçali Formation (limestone)	137, 437, 517
Kozluca Formation (conglomerate, sandstone, marl)	537
Kömürlü Formation (marl, claystone, siltstone)	437, 517, 537
Lice Formation (limestone)	137, 437, 537
Lower Sinan Formation (limestone)	517
Mardin Formation (dolomite, siltstone, sandy limestone)	517, 537
Midyat Formation (limestone, sandstone)	111, 135, 137, 437, 517
Midyat Group (limestone, sandstone)	137, 437, 517, 537
Norman Formation (marl, limestone)	137, 437
Sabunsuyu Formation (limestone, dolomite)	517, 537
Sipikör Formation (limestone, shale)	517, 537
Telhasan Formation (conglomerate, sandstone)	537
Terbüzek Formation (pebbly sandstone, shale)	137, 437, 517
Uludere Formation (limestone)	537, 617, 637
Upper Sinan Formation (bioclastic limestone)	517
Yolaçan Formation (limestone, dolomite)	537
Zırnak Formation (limestone, sandstone)	114, 117, 137, 437, 517, 537

Appendix 2. IADC codes of tricone bits used in other formations in the Thrace Basin

Formation	IADC Codes of Tricone Bits
Ceylan Formation (clayey limestone, sandstone, shale)	137, 437
Çanakkale Formation (claystone, sandstone, siltstone)	437, 517
Çekmece Formation (mudstone, sandstone, marl, limestone)	137, 437, 517
Gaziköy Formation (shale, sandstone)	137, 517, 537
Hamitabat Formation (conglomerate, sandstone, shale)	437, 517
Keşan Formation (marl, shale, sandstone)	111, 137, 437
Mezardere Formation (shale, marl, tuff)	137, 437, 517
Soğucak Formation (limestone)	437, 517
Trakya Formation (conglomerate, sandstone)	137, 437

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